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377800

VOLUME IX E ENGINE (U)
Part 2 Technical
Section F Manufacturing Techniques and Materials
Phase II-A Data Submission

Prepared for

Office of Deputy Administrator for Supersonic Transport Development
Federal Aviation Agency
Washington, D. C.

November 1, 1964

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TABLE OF CONTENTS

1. MANUFACTURING TECHNIQUES

In general, the STF219 design configuration does not present unusually difficult manufacturing problems. Although some of the parts differ geometrically from existing engines, they use materials which are successfully machined, welded, heat and surface treated, etc., as a normal part of Pratt & Whitney Aircraft factory activity. The major portion of the engine can be classified a "standard" to Pratt & Whitney Aircraft production departments due to the experience gained with the TF30, J58, and thrust reverser parts and assemblies.

1.1 Blades and Vanes

Air-cooled turbine vanes are presently being manufactured by Pratt & Whitney Aircraft for use in the TF30 and J58 engines.

The STF219 design calls for more complex machining practices. Slots in the leading edge of turbine blades and vanes present no major problem; these slots may be integrally cast or electrochemical and electrodischarge machining can be used. Electron beam drilling of very small holes is now being developed, and is proving satisfactory for the installation of the air holes or slots in the trailing edge. The electron beam and normal fusion welding and the brazing required by the various airfoil designs either currently falls within standard Pratt & Whitney Aircraft production practices or are projections of same.

1.2 Surface Coatings

Supplemental surface coatings, which are applied to increase the useful life of jet engine parts, have been in use for some time at Pratt & Whitney Aircraft. Intensive development work and testing programs have yielded several methods by which these coatings can be applied. These methods include application of a slurry of metal powder in a suitable vehicle which is then diffused into the surface of the base metal, applying molten metals and metal carbides or oxides using an oxyacetylene flame torch or using an ionized gas (plasma) torch system. Many types of materials are coated ranging from stainless steels, nickel, and cobalt base alloys to titanium alloys. Typical coating materials are aluminum, molybdenum, nickel-aluminide, and various metal oxides and carbides.

A recent innovation is the manufacture of turbine seals using a metal sprayed porous abradable coating, which permits more efficient operation of the turbine section of gas turbine engines through

reduced operating clearances.

At present there are two plasma spray installations in the production plus one unit which is in use for continuing development work. There are also various types of flame spraying equipment in use. Additional plasma spray equipment is being procured to meet the increasing demand for the application of these coatings to engine parts.

1.3 Use of Titanium

The forward portion of the STF219 engine is largely titanium. This includes such items as:

- Fan Cases
- Fan Blades
- Fan Discs
- 2nd Stage Vane & Shroud Assemblies
- High Compressor Guide Vanes
- Fan Diffuser Ducting
- Outer Duct Cases

Pratt & Whitney Aircraft initiated the use of titanium alloys in its engines over ten years ago. Today, after a great deal of development, machining such as turning, grinding, drilling, broaching, etc. has become very common to our production. Through the careful control of the metallurgical properties of alloys and welding atmospheres, the "in line" production of quality heat-treated aircraft weldments is now routine.

1.4 Compressor Section

This compressor section is similar to the J58 compressor, which is currently in production. The advanced design of integral spacer to fan disk and integral spacer to turbine disk call for contour turning, which is standard machining practice at Pratt & Whitney Aircraft.

1.5 Intermediate Case

This case presents average complexity of heat treating and machining problems. 54" O.D. cases can be handled on conventional turning, boring and profiling equ ment using standard processing.

1.6 Burner Assembly

The annular burner for the STF219 engine presents no particular

problem. It is a Hastelloy "X" weldment, that will be processed to allow sufficient material for weld shrinkage and for machining. Smaller parts will be machined from forgings and castings. The sheet metal will be formed on presses and sized by sizing machines. We have had considerable experience in all phases of this type of fabrication.

1.7 Shroud Containment Rings on the 3rd and 7th Stage Compressor Blades

Although the use of containment rings for retaining blades in the discs is an advanced design, present equipment and processes allow the machining of 30" diameter rings to close tolerances. Grinding tolerances and flatness and surface finishes can be maintained to meet design requirements.

1.8 Floating Seal

The floating seal at the rear of the high pressure compressor follows conventional turning and grinding. Mechanical air seals and labyrinth seals are widely used in this engine. Pratt & Whitney Aircraft has used this type of seal in most turbine engines, and has developed highly specialized cutting tools for machining these configurations.

1.9 Outer Compressor Duct

Skip milling or skip turning is required on this part to form the joining flanges and 2 bosses. This process is an approved method of machining and currently applied to the TF30 engine diffuser duct and similar parts.

1.10 Exhaust Nozzle Section

This section is similar to the TF30 engine nozzle.

1.11 Duct Heater

The design of the corrugated inner section which is resistance welded to the outer skin, is the same type of construction that is now being used on the JT11 combustion chamber case-inner assembly.

1.12 The Thrust Reverser

This section is made up of pie shaped plates with standard draw bars

and hydraulic actuators. These items are similar to the afterburner doors which Pratt & Whitney Aircraft are manufacturing for the JT4 and other type engines.

1.13 Cases with Airfoil Buttresses for Welded Struts, etc.

The buttress configuration will be machined by the electro-chemical method. The lightening slots in the buttresses are produced by the electrodischarge method. Both of these methods are highly developed and are in regular production use at Pratt & Whitney Aircraft on the JT8D and TF30 engines.

1.14 Assembly

The manufacture of the JT8D engine has provided considerable assembly experience on full ducted fan engines. No unusual difficulties are anticipated with the STF219 outer duct design. The majority of the engine is amenable to standard Pratt & Whitney Aircraft assembly practices.

The assembly and balancing of "overhung" compressor (3rd) and fan stages are accomplished on the JT8D engine. The STF219 will be handled similarly.

2. MATERIALS

The materials selected for major components of the STF219 engine are listed in Tables F2-1 and F2-2. Table F2-1 also shows the materials previously proposed for the JT11F-11 and JT11F-12 in the Phase I Report, and an indication of the reason for any differences between the Phase I and Phase II-A Reports. Table F2-2 relates these materials to applications in current Pratt & Whitney Aircraft engines.

TABLE F2-1

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal (1) JT11F-11 Mach 2.5-2.7	Previous Proposal (1) JT11F-12 Mach 3.0	Reason for Difference
FAN SECTION					
Front Mount Ring	PWA 1202	PWA 1202	-	-	
Fan Cases	PWA 1202	PWA 1202	Same (2)	Same (3)	No comparable part
Hub	PWA 1202	PWA 1202	-	-	No comparable part
Blade-1st Stage	AMS 4928	AMS 4928	PWA 1202	PWA 1202	To avoid possible stress-corrosion
Blade-2nd Stage	AMS 4928	AMS 4928	PWA 1202	PWA 1202	
Disk-1st Stage	PWA 1202	PWA 1203	Same	Same	
Disk-2nd Stage	PWA 1202	PWA 1203	Same	Same	
Vane-1st Stage	PWA 1202	PWA 1202	AMS 4910	AMS 4910	
Shroud, Inner 1st Stage	AMS 4926	AMS 4926	Same	Same	Different construction
	AMS 4910	AMS 4910			
Vane-2nd Stage	PWA 1202	PWA 1202	Same	PWA 1203	
Shroud, Inner 2nd Stage	PWA 1202	PWA 1202	Same	PWA 1203	Different construction
Shroud, Outer 2nd Stage	AMS 4926	AMS 4926	PWA 1202	PWA 1203	
	AMS 4910	AMS 4910			
Vane, Fan Exit Guide	AMS 5667	AMS 5667	AMS 4966	AMS 4966	Different construction
INTERMEDIATE SECTION					
Main Bearings					
-Balls and Races	AMS 6490	AMS 6490	Same	Same	
-Cages	AMS 6415	AMS 6415	Same	Same	
Bearing Support	AMS 5613	AMS 5613	Same	Same	
Seal Support Assy's	AMS 5613	AMS 5613	Same	Same	
Intermediate Case	AMS 5616	AMS 5616	-	-	
Towershaft Bearings					No comparable part
-Balls, Rollers and Races	PWA 724 CVM or AMS 6490	PWA CVM or AMS 6490	Same	Same	
-Cages	AMS 6415	AMS 6415	Same	Same	
Towershaft	PWA 724	PWA 724	AMS 6263	AMS 6263	Improved case hardness retention in hot oil
Gears	PWA 724	PWA 724	AMS 6260	AMS 6260	
Vane, High Comp. Inlet Guide	PWA 1202	PWA 1202	-	-	No comparable part

(1) Ref. Vol. E-VIII, Table 1-1
(2) Same as STF219 Mach 2.7
(3) Same as STF219 Mach 3.0

TABLE F2-1 (Cont)

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal JT11F-11 Mach 2.5-2.7	Previous Proposal JT11F-12 Mach 3.0	Reason for Difference
HIGH COMPRESSOR SECTION					
Blade-3rd Stage	PWA 1003	PWA 1003	PWA 1202	Same	Higher temp. and stress
Blade-4th Stage	PWA 1003	PWA 1003	PWA 1202	Same	Higher temp. and stress
Blade-5th Stage	PWA 1003	PWA 1003	Same	Same	
Blade-6th Stage	PWA 1003	PWA 1007	Same	Same	
Blade-7th Stage	PWA 1003	PWA 1007	Same	Same	
Disk-3rd Stage	PWA 1003	PWA 1003	Same	Same	
Disk-4th Stage	PWA 1003	PWA 1003	Same	Same	
Disk-5th Stage	PWA 1003	PWA 1007	Same	PWA 1003	Higher temp. and stress
Disk-6th Stage	PWA 1003	PWA 1007	Same	Same	
Disk-7th Stage	PWA 1007	PWA 1013	PWA 1003	Same	Higher temp. and stress
Spacer Inner 3rd-4th	PWA 1003	PWA 1003	Same	Same	
Spacer Inner 4th-5th	PWA 1003	PWA 1003	Same	Same	
Spacer Inner 5th-6th	PWA 1003	PWA 1007	Same	Same	
Spacer Inner 6th-7th	PWA 1007	PWA 1013	PWA 1003	Same	Higher temp. and stress
Spacer Outer 3rd-4th	PWA 1003	PWA 1003	Same	Same	
Spacer Outer 4th-5th	PWA 1003	PWA 1007	Same	Same	
Spacer Outer 5th-6th	PWA 1003	PWA 1007	Same	Same	
Spacer Outer 6th-7th	PWA 1007	PWA 1013	PWA 1003	Same	Higher temp. and stress
Front Hub	PWA 1003	PWA 1003	AMS 6304	AMS 6304	Higher temp.
Rear Hub	PWA 1003	PWA 1003	PWA 1010	PWA 1010	New design allows economy
Tie Bolt	PWA 90	PWA 90	Same	Same	
Seal Disk	PWA 1003	PWA 1007	Same	PWA 1013	New design allows economy
Vane-3rd Stage	AMS 5667	AMS 5667	AMS 5616	Same	Improved corrosion resistance
Vane-4th Stage	AMS 5667	AMS 5667	AMS 5616	Same	
Vane-5th Stage	AMS 5667	PWA 687	Same	AMS 5667	Higher temp.
Vane-6th Stage	PWA 687	PWA 687	AMS 5667	AMS 5667	Higher temp.
Vane, Exit Guide	AMS 5754	AMS 5754	AMS 5667	PWA 687	Different construction
Shroud, Inner 3rd Stage	AMS 5667	AMS 5667	AMS 5616	Same	Improved corrosion resistance
Shroud, Inner 4th Stage	AMS 5667	AMS 5667	AMS 5616	Same	
Shroud, Inner 5th Stage	AMS 5667	AMS 5668	Same	AMS 5667	Higher temp.
Shroud, Inner 6th Stage	AMS 5668	PWA 1004	AMS 5667	AMS 5667	Higher temp.
Shroud, Inner Exit Guide	AMS 5754	AMS 5754	Same	Same	
Inner Seal	AMS 5754	AMS 5754	Same	Same	
Case Outer 3rd Stage	AMS 5667	AMS 5667	AMS 5616	Same	Improved corrosion resistance
Case Outer 4th Stage	AMS 5667	AMS 5667	AMS 5616	Same	

TABLE F2-1 (Cont)

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal JT11F-11 Mach. 2.5-2.7	Previous Proposal JT11F-12 Mach 3.0	Reason for Difference
HIGH COMPRESSOR SECTION (Cont)					
Case Outer 5th Stage	AMS 5667	AMS 5667	Same	Same	
Case Outer 6th Stage	AMS 5667	AMS 5667	Same	Same	
Case Outer Rear	AMS 5667	AMS 5667	-	-	No comparable part
Shroud, Outer exit Guide	AMS 5754	AMS 5754	Same	Same	
DIFFUSER AND COMBUSTION SECTION					
Diffuser Case, Inner and Outer	PWA 1033 PWA 1009	PWA 1030 PWA 687	Same	PWA 1033 PWA 1009	Higher temp.
Comb. Case - Outer Forward	PWA 1009	PWA 687	Same	Same	
Comb. Case - Outer Rear	PWA 1009	PWA 687	Same	Same	
Comb. Case - Inner Forward	PWA 1004	PWA 1004	Same	Same	
Comb. Case - Inner Rear	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
Comb. Liners	AMS 5536	AMS 5536	Same	Same	
Fuel Manifold	AMS 5646 PWA 1060	AMS 5646 PWA 1060	Same	Same	
Fuel Nozzle	AMS 5616	AMS 5616	Same	Same	
Bearing Rollers	PWA 724 CVM or AMS 6490	PWA 724 CVM or AMS 6490	-	-	No comparable part
Bearing Races	PWA 724 CVM or AMS 6490	PWA 724 CVM or AMS 6490	-	-	No comparable part
Bearing Cage	AMS 6415	AMS 6415	-	-	No comparable part
Bearing Support, Inner	AMS 5613	AMS 5613	-	-	No comparable part
Bearing Support, Outer	PWA 687	PWA 687	-	-	No comparable part
Seal Supports, Inner	AMS 5613	AMS 5613	-	-	No comparable part
Seal Supports, Outer	AMS 3667	AMS 5667	-	-	No comparable part
TURBINE SECTION					
Case-Outer Front and Rear	PWA 1004	PWA 1004	Same	Same	
Shaft, Low Turbine	PWA 1003	PWA 1003	-	-	No comparable part
Front Coupling	PWA 1003	PWA 1003	Same	Same	
Shaft, High Turbine	PWA 1003	PWA 1003	PWA 1010	PWA 1010	New design allows economy

TABLE F2-1 (Cont)

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal JT11F-11 Mach 2.5-2.7	Previous Proposal JT11F-12 Mach 3.0	Reason for Difference
TURBINE SECTION (Cont)					
Vane-1st Stage	PWA 653	PWA 653	PWA 637	PWA 687	
Vane-2nd Stage	PWA 658	PWA 658	PWA 659	PWA 659	
Vane-3rd Stage	PWA 658	PWA 658	PWA 655	PWA 655	
Blade-1st Stage	PWA 658	PWA 658	PWA 659	PWA 659	See Section 2.1 and 2.2
Blade-2nd Stage	PWA 658	PWA 658	PWA 659	PWA 659	
Blade-3rd Stage	PWA 658	PWA 658	PWA 655	PWA 655	
Disk-1st Stage	PWA 1007	PWA 1007	PWA 1003	PWA 1003	Higher temp.
Disk-2nd Stage	PWA 1003	PWA 1007	Same	PWA 1003	Higher temp.
Disk-3rd Stage	PWA 1003	PWA 1007	Same	PWA 1003	Higher temp.
Hub-Low Turbine	PWA 1003	PWA 1003	Same	Same	
Seal-Outer 1st Stage Tip	AMS 5754	AMS 5754	Same	Same	
Seal-Outer 2nd Stage Tip	AMS 5754	AMS 5754	Same	Same	
Seal-Outer 3rd Stage Tip	AMS 5754	AMS 5754	Same	Same	
Inner Shroud, Diaphragms and Seals -1st Stage	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
Inner Shroud, Diaphragms and Seals -2nd Stage	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
Inner Shroud, Diaphragms and Seals -3rd Stage	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
Outer Disk Spacer	PWA 1007	PWA 1007	PWA 1003	PWA 1003	Higher temp.
Tiebolts	PWA 90	PWA 90	Same	Same	
TURBINE EXHAUST SECTION					
Case-Turbine Exhaust Assembly	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
Heatshields-Exhaust Case Structure	AMS 5536	AMS 5536	Same	Same	
Tailcone	AMS 5536	AMS 5536	Same	Same	
Duct-Exhaust	PWA 687 PWA 1030	PWA 687 PWA 1030	Same	Same	
REAR BEARING SECTION					
Rollers	PWA 724 CVM or AMS 6490	PWA 724 CVM or AMS 6490	Same	Same	
Races	PWA 724 CVM or AMS 6490	PWA 724 CVM or AMS 6490	Same	Same	

TABLE F2-1 (Cont)

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal JT11F-11 Mach 2.5-2.7	Previous Proposal JT11F-12 Mach 3.0	Reason for Difference
REAR BEARING SECTION (Cont)					
Cages	AMS 6415	AMS 6415	Same	Same	
Bearing Support	PWA 1004	PWA 1004	AMS 5613	AMS 5613	Different construction
Seal Support Assy	AMS 5613	AMS 5613	Same	Same	
FAN DIFFUSER SECTION					
Duct, Liner	AMS 4910	AMS 4910	Same	Same	
Duct, Outer	AMS 4966	AMS 4966	Same	Same	
Struts	AMS 4910	AMS 4910	-	-	No comparable part
	AMS 4966	AMS 4966			
Turning Vanes	AMS 4910	AMS 4910	-	-	No comparable part
DUCT HEATER SECTION					
Case-Forward	PWA 1202	PWA 1202	AMS 4910	AMS 4910	Different construction
Case-Rear Mount	PWA 1202	PWA 1202	-	-	No comparable part
Case-Rear	AMS 5508	AMS 5508	AMS 4910	AMS 4910	Different construction
	AMS 5616	AMS 5616			
Front Liner-Inner and Outer	AMS 5536	AMS 5536	Same	Same	
Rear Liner-Inner and Outer	PWA 95	PWA 95	Same	Same	
Flame Holder	AMS 5754	AMS 5754	Same	Same	
Spray Rings	AMS 5754	AMS 5754	Same	Same	
Heatshield, Rear Mount	AMS 5536	AMS 5536		-	No comparable part
DUCT NOZZLE SECTION					
Unison Ring	AMS 4910	AMS 4910	PWA 1033	PWA 1033	Different construction
	AMS 4966	AMS 4966	PWA 1009	PWA 1009	
Flaps - Nozzle	PWA 658	PWA 658	Same	Same	
Seal Segments-Radial	AMS 5540	AMS 5540	AMS 5504	AMS 5504	(Typographical error)
Actuators-Hydraulic	AMS 5643	AMS 5643	AMS 5616	AMS 5616	Improved corrosion resistance

TABLE F2-1 (Cont)

MATERIALS FOR GAS TURBINE ENGINE FOR SUPERSONIC TRANSPORT

	STF219 Mach 2.7 65,000'	STF219 Mach 3.0 65,000'	Previous Proposal JT11F-11 Mach 2.5-2.7	Previous Proposal JT11F-12 Mach 3.0	Reason for Difference
REVERSER					
Ejector Shroud Assembly	AMS 5542	AMS 5542	PWA 1033	PWA 1033	New design allows economy
	AMS 5667	AMS 5667	PWA 1010	PWA 1010	
Blow-In Doors Front	AMS 4910	AMS 4910	AMS 5525	AMS 5525	
Blow-In Doors Rear	AMS 4910	AMS 5525	AMS 5525	Same	Lower temp.
Reverser Flaps	PWA 655	PWA 655	PWA 658	PWA 658	Lower temp.
Reverser Links	AMS 5582	AMS 5582	PWA 1061	PWA 1061	Lower temp
	AMS 5667	AMS 5667			Lower temp.
Trailing Edge Flaps	PWA 1030	PWA 1030	Same	Same	
	PWA 687	PWA 687	AMS 5536	AMS 5536	Different construction
Actuators, Hydraulic	AMS 5643	AMS 5643	AMS 5616	AMS 5616	Improved corrosion resistance

TABLE F2-2

PROPOSED SST MATERIALS RELATED TO CURRENT ENGINE APPLICATIONS

TITANIUM ALLOYS	Specifications	Engines Where Used Currently	Major Component in SST Engine
A110AT	AMS 4910 Sheet AMS 4926 Bars AMS 4966 Forgings	J57, JT3, J75, JT4, TF30	Fan stator shrouds, rotor blades Fan diffuser duct weldment Reverser-ejector blow-in doors
Ti-8Al-1Mo-1V	PWA 1202 Forgings PWA 1204 Bars	JTF10, JT11, TF30	Mount rings Fan cases Vanes and shrouds Fan disks, hub High compr. inlet vanes
Ti-5Al-5Zr-5Sn	PWA 1203 Bars, forgings	Experimental	Fan compressor disks
ALLOYS STEELS			
Bower 315 (vacuum melted)	PWA 724 CVM Bars, forgings	JT3D, JT8D, TF30, JT11	Roller bearings, races
M-50 (vacuum melted)	AMS 6490 Bars, forgings, tubing	JT3D, JT8D, TF30, JT11	Ball and roller bearings, races
STAINLESS STEELS			
AISI 410 (12 Cr)	AMS 5504 Sheet AMS 5613 Bars, forgings AMS 5591 Seamless tubing	All	Bearing support weldments Seal support weldments
Greek Ascoloy (12Cr-2Ni-3W)	AMS 5616 Bars, forgings AMS 5508 Sheet	All	Compressor intermediate case Duct heater case Fuel nozzles
AISI 321	AMS 5645 Bars, forgings AMS 5510 sheet AMS 5570 Seamless tubing	All	Air and oil lines

TABLE F2-2 (Cont)

PROPOSED SST MATERIALS RELATED TO CURRENT ENGINE APPLICATIONS

	Specifications	Engines Where Used Currently	Major Component in SST Engine
STAINLESS STEELS (Cont)			
AISI 347	AMS 5646 Bars, forgings AMS 5512 Sheet AMS 5571 Seamless tubing	All	Air and oil lines Fuel line fittings
NICKEL ALLOYS			
Inconel	PWA 1060 Seamless tubing AMS 5540 Sheet AMS 5665 Bars, forgings	All	Fuel Lines Heat shields
Hastelloy X	AMS 5536 Sheet AMS 5754 Bars, forgings	All	Compr. exit guide vanes and shrouds Burner liners Transition duct Turbine blade tip seals Tailcone, duct heater liner Heatshields Spray ring assemblies
N-155 Rigimesh	PWA 95 Porous strip, sintered	JT11	Duct heater liner
Inconel X	AMS 5667 Bars, forgings AMS 5668 Bars, forgings AMS 5542 Sheet	All	Fan exit guide vanes Compressor vanes and shrouds Seal support weldments Reverser-ejector shroud assy and links
Inconel 718	PWA 1009 Bars, forgings PWA 1010 Bars, forgings PWA 1033 Sheet	TF30, JT11	Diffuser case weldment Combustion case weldments

TABLE F2-2 (Cont)

PROPOSED SST MATERIALS RELATED TO CURRENT ENGINE APPLICATIONS

	Specifications	Engines Where Used Currently	Major Component in SST Engine
NICKEL ALLOYS (Cont)			
Incoloy 901	PWA 1003 Forgings	All	Compressor blades, disks, spacer, hubs Turbine disks, spacers, hubs shafts
Waspaloy	PWA 687 Bars, forgings PWA 1004 Bars, forgings PWA 1007 Forgings PWA 1030 Sheet PWA 90 Bolts	All	Compressor vanes and shrouds Compressor blades, disks, spacers Tiebolts Combustion case weldments Turbine disks and spacer Turbine cases, shrouds, ducts
Astroloy	PWA 1013 Forgings	JT11	Compressor disks, spacers
IN-100	PWA 658 Investment castings	JT11	Turbine blades 2nd and 3rd stage turbine vanes Duct heater nozzle flaps
SM 200	PWA 659 Investment castings	JT11	Turbine blades (alternate) 2nd and 3rd stage turbine vanes (alternate)
PWA 663	PWA 663 Investment castings	Experimental	Turbine blades (alternate) Turbine vanes (alternate)
Inconel 713	PWA 655 Investment castings	J52, JT8, TF30	Reverser flaps
COBALT ALLOYS			
WI-52	PWA 653 Investment castings	J52, JT8, JT3, TF33, GG4, JT12	1st Stage turbine vanes

2.1 Turbine Blades

A primary factor in the development of turbojet engines having improved thrust ratings has been the development of turbine blade alloys with mechanical and physical properties capable of withstanding the high temperatures and stresses involved. Early in the development of the J48 centrifugal compressor turbojet engine it became apparent that the properties of the current turbine blade alloy, Nimonic 80A, limited the performance and hindered the development of advanced powerplants. The attainment of increased thrust ratings was closely linked to the development by Pratt & Whitney Aircraft of a new nickel-base precipitation hardening alloy. This alloy was the original Waspaloy, with the following composition - 19.5Cr, 13.5Co, 3.5Mo, 2.5Ti, 1.2Al, balance nickel. Initial development efforts were concerned with defining the composition, directing programs at the fabricators leading to improvements in melting and forging practice, and establishing the heat treatment which is basic for this and similar alloys. This alloy system proved to be so successful that it formed the basis for a family of forged alloys, including Udimet 500 and Udimet 700, which are basically similar to Waspaloy, but with higher hardener contents (Ti and Al). With each level of increase of strength due to additional alloying elements, the forgeability of the material was reduced. Beyond the Udimet 700 composition a family of nickel-base alloys has been developed which achieved such high creep and rupture strength that the alloys are currently considered non-forgeable and therefore are employed as castings. The relationship of forgeability to composition is illustrated schematically in Figure F2-1. During the period of development of the family of nickel-base superalloys, performance improvements of Pratt & Whitney Aircraft turbojet engines have been realized because of the development of higher-strength, higher-temperature, better quality, and more reliable alloys. To illustrate this, the temperature capability of these alloys has increased more than 300°F from 1947 to 1964. This progress is shown in Figure F2-2.

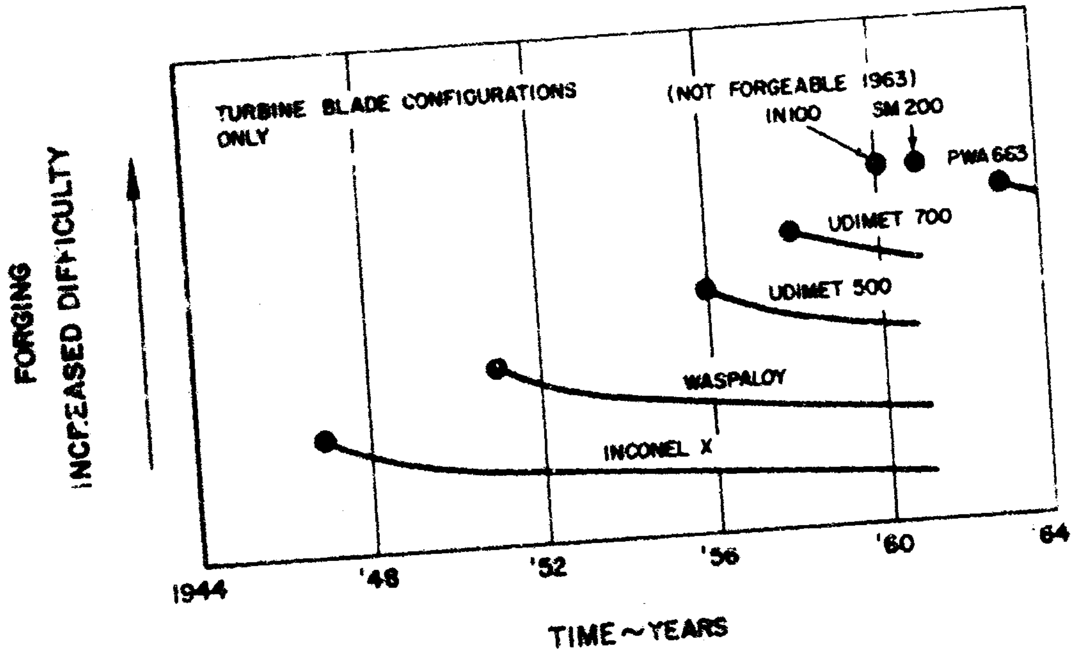

Figure F2-1 Progress in Nickel-Base Alloy Forging Development

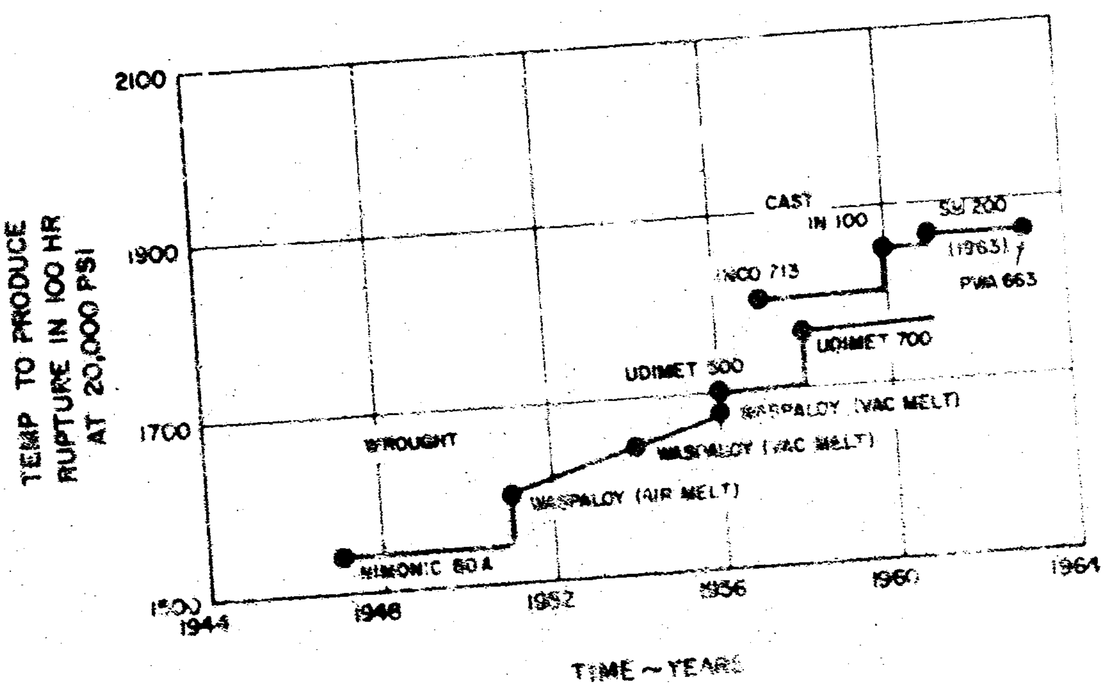

Figure F2-2 Progress in Nickel-Base Alloy Development

2.1.1 Alloy Selection for the SST Turbine Blades - Selection of the alloy for the turbine blades of the SST engine is based on successful JT11 (J58) engine experience, which was in turn based on thousands of hours of laboratory and test rig evaluation. The results of this testing are discussed in Section 15 of the Final Contract Report. Primary factors evaluated in these extensive Pratt & Whitney Aircraft materials programs include:

- Mechanical properties at elevated temperatures
  - Creep and stress-rupture strength and ductility
  - Tensile strength and ductility
  - Fatigue behavior of test bars and prototype blades
- Thermal fatigue, both coated and uncoated
- Oxidation-corrosion and erosion resistance
- Coating requirements for high temperature operation
- Metallurgical stability during long exposures to temperature and stress
- Reliability of castings as related to melting, casting and quality control practices.

Based on an analysis of such factors as detailed above, three nickel-base alloys, PWA 658 (IN 100), PWA 659 (SM 200), and PWA 663, are proposed as the most promising candidates for first, second, and third stage turbine blades. PWA 658, 659 and 663 are complex nickel-base casting alloys which derive their strengths from dispersions of carbides and Ni_3 (Ti, Al, M) type intermetallic compounds. Nominal compositions and stress-rupture acceptance requirements of the alloys are listed in Tables F2-3 and F2-4.

TABLE F2-3

ALLOY COMPOSITION

Alloy	Type	Composition
PWA 658	Nickel-base	9.5Cr-15Co-3Mo-4.8Ti-5.5Al-1V-0.015B-0.06Zr
PWA 659	Nickel-base	9Cr-10Co-12.5W-1Cb-2Ti-5Al-0.015B-0.05Zr
PWA 663	Nickel-base	8Cr-10Co-6Mo-4.3Ta-1Ti-6Al-0.015B-0.07Zr

TABLE F2-4

PWA SPECIFICATION REQUIREMENTS FOR

STRESS-RUPTURE PROPERTIES

Alloy	Temp.	Stress	Life (min.)	Elongation (min.)
PWA 658	1800F	29,000psi	23 Hrs.	4%
	1400	85,000	23	2
PWA 659	1800	29,000	23	3
	1400	94,000	23	1
PWA 663	1800	29,000	30	3
	1400	94,000	23	1

(Elongation at 1400F is determined 2 hours before rupture).

The PWA 658 alloy selected as the primary candidate material for the three turbine stages has been demonstrated to be a highly reliable creep-resistant, commercially available cast material by considerable rig, experimental engine, and accumulated service experience in J58 engines. The alloy is readily castable into the intricate configurations required for cooled turbine blades. Furthermore, though it possesses high creep-rupture strength in the cast condition, a 1600°F heat-treatment for 12 hours significantly improves the 1400 and 1800°F creep-rupture properties over the as-cast condition. The most significant improvement in PWA 658 properties occurs in 1400°F creep-rupture life and prior creep elongation. This is of primary importance, since the 1400°F ductility of nickel-base alloys is often a limiting factor, particularly when highly stressed configurations such as blade roots are to operate at this temperature.

Materials design criteria for turbine blade alloys are based on creep and rupture data for the proposed operating temperatures. Time to 1 per cent creep is one of the limiting factors in blade design, and it defines the capability of any alloy to withstand long time operation. In addition to strength to resist the tendency to creep at high temperatures, a useful alloy must have sufficient ductility to resist the adverse effects of stress concentration. Using fundamental information of this type, the designer must then provide for supplemental cooling, where operating conditions require gas temperatures which are incompatible with the

long-time, high-temperature properties of the material. Conventional creep and rupture tests unfortunately show only the effects of steady stress and temperature on the deformation behavior of an alloy. Thermal gradients produced in both cooled and uncooled parts have a significant effect on the alloy's performance, but do not yield themselves to simple prior analysis. Pratt & Whitney Aircraft has built up a tremendous fund of practical experience on the applicability and reliability of both cast and wrought nickel alloys under many varied conditions of engine operation, and is, therefore, fully aware of the limitations of these systems. Continual studies of effects of thermal gradients associated with air cooling, combined stress fatigue, and thermal fatigue supplement standard creep, rupture, and fatigue testing in order to understand more fully the complex behavior of turbine blade materials.

Oxidation, sulphidation, corrosion, and erosion resistance are also of importance. Because these material properties as revealed by conventional laboratory methods often do not correlate with behavior exhibited in an actual engine, new testing methods have had to be devised. The rotating specimen rig, pictured in Figure F2-3 shows one type of apparatus. This rig is capable of simultaneously exposing several samples of promising blade or vane materials and coatings to high velocity, high temperature gases, with or without additives, to simulate engine service. Through laboratory rig tests and experimental engine tests, the sources of failure in the cobalt-and nickel-base alloy systems have been defined. It has been found that coatings could be tailored to retard sulphidation, erosion, corrosion, and thermal fatigue triggered by oxidation at grain boundaries. One of the significant results of this program has been the development by Pratt & Whitney Aircraft of an aluminum-silicon coating (PWA 47) which is used to protect nickel-base turbine blades from intergranular oxidation. The effectiveness of this coating in protecting the metal surface is illustrated in Figure F2-4. A high temperature diffusion cycle is employed to produce a layer of intermetallic compounds closely controlled in thickness. The coated surface is an effective barrier against surface reactions generated by the combusted gases. The factors which limit coating life, exclusive of the prospect of foreign particle damage, are the physical changes associated with the diffusion mechanism, the surface melting temperature, and the erosion resistance of the coating. The PWA coating is known to melt at approximately 2100°F and the test data which have been collected under rig tests predict that metal surface temperatures should not exceed 1900°F for extended engine operation. Test data in excess of 1400 hours at 1700°F have demonstrated that the PWA coating maintains its integrity with no significant signs of distress. Because of the importance of coatings in the operation of nickel alloy hardware at temperatures above 1700°F, Pratt & Whitney Aircraft has maintained a development

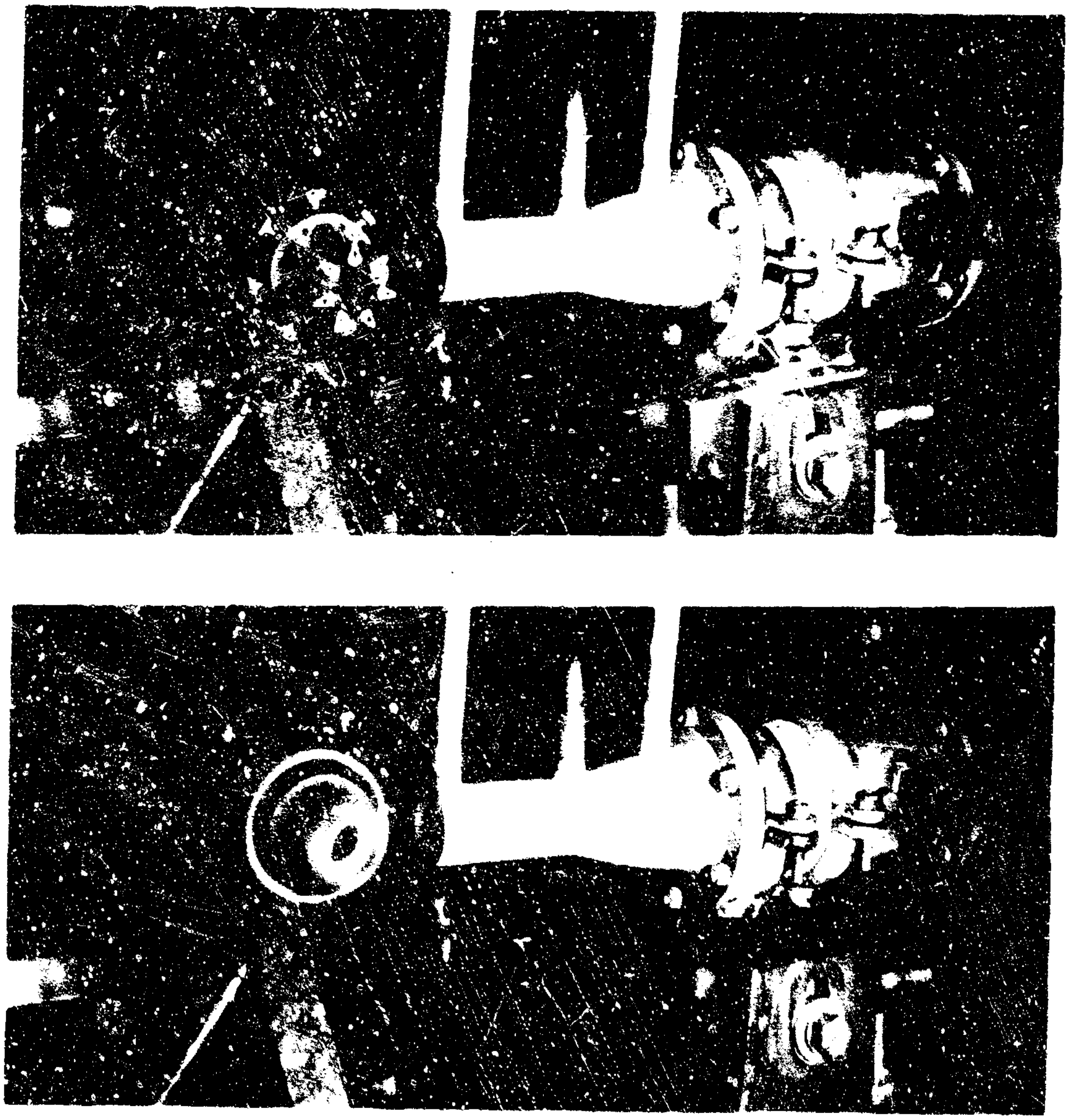

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Figure F2-3. Rotating Specimen Rig

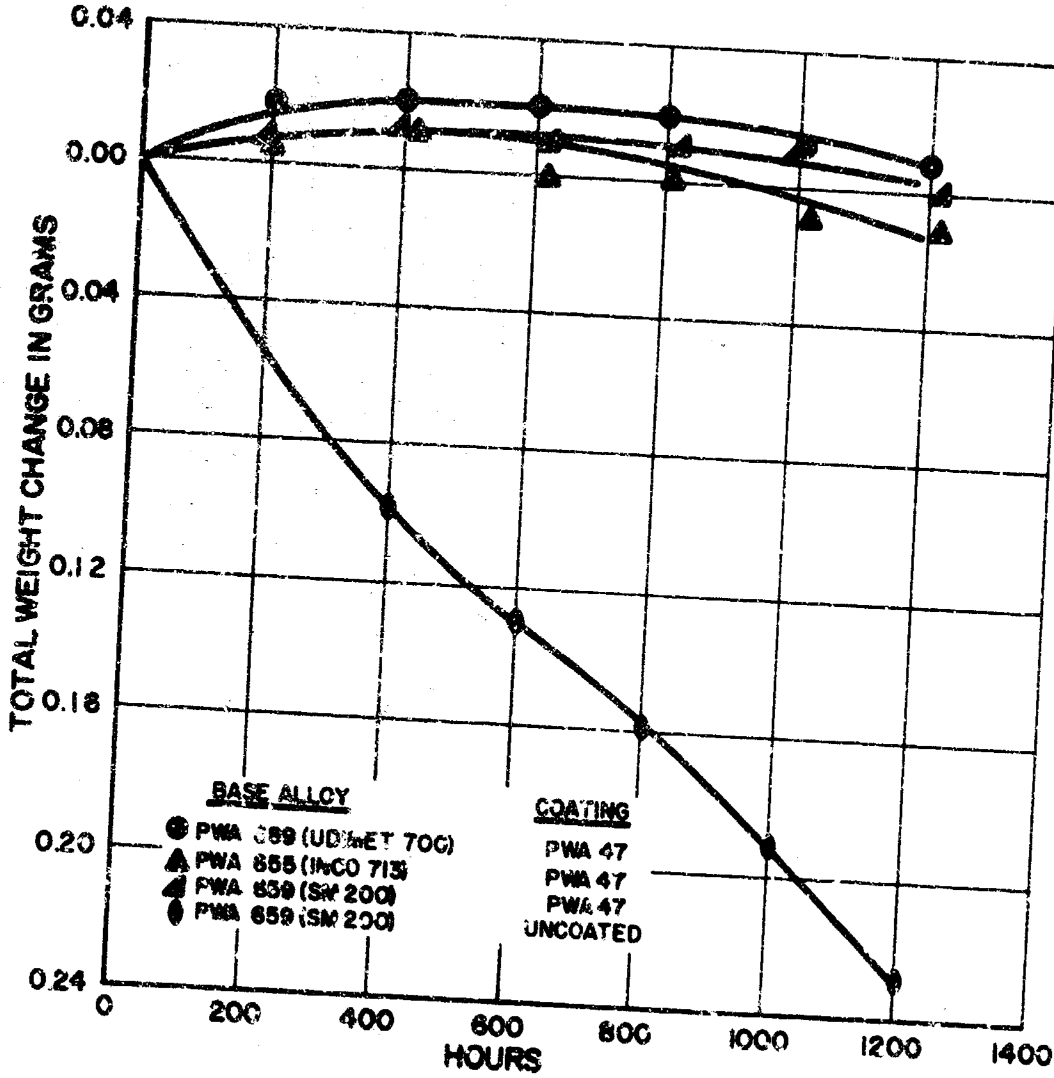

Figure F2-4. Effect of Pratt & Whitney Aircraft Coatings on 1000 Hour Erosion Properties of Three Nickel - Base Alloy Turbine Materials at 1700°F

program aimed at increasing the effectiveness of coating-base metal protective systems. One coating, on which many hundreds of hours of rig data are available, has a 200°F melting point advantage over the present commercially used PWA 47 coating.

Metallurgical stability during long time exposure to temperature and stress has been of concern in commercial operation with the precipitation hardening nickel-base alloys, chiefly Waspaloy, Udimet 500 and Udimet 700. Pratt & Whitney Aircraft has conducted extensive electron metallographic and microprobe phase identification studies of carbide, boride, and sigma phases in both wrought and cast blade alloys. These

results are presented in Section 15 of the Final Contract Report. Overaging and attendant loss of rupture strength, as well as embrittlement due to (a) precipitation of $M_{23}C_6$ or M_6C carbides at grain boundaries, or (b) duplexed grain structure resulting from forging and intergranular cracks associated with creep deformation mechanisms, have been encountered. Although Pratt & Whitney Aircraft has millions of hours of commercial and military experience on wrought and cast nickel alloys, it continus to direct considerable attention towards defining the effects of the above factors in order to extend the useful life of wrought turbine blade material and to improve the temperature-time capability of the cast nickel alloys.

The two alternate cast alloys, PWA 659 and PWA 663, considered for turbine blade application have also undergone extensive rig and experimental engine testing. Comparison of all three cast alloys on the basis of stress for 1 per cent creep at 1600°, 1700° and 1800°F indicates that PWA 659 is more creep resistant than PWA 658 or PWA 663 for times of 1000 to 10,000 hours. These results are shown in Figures F2-5 to F2-7. These materials are considered on the more realistic basis of strength-density relationship in Figures F2-8 through F2-10. The cast alloys are more nearly equivalent in strength-density.

The PWA 659 alloy has performed favorably in advanced JT-4 and JT-11D engines. PWA 663 also has experienced engine tests in JT-8 and TF33 engines, showing impressive performance in creep and thermal fatigue. Although PWA 659 shows superiority in creep and thermal stability to all other cast alloys, the alloy shows lower creep ductility at intermediate temperatures (1200° to 1400°F). Since PWA 659 and PWA 663 alloys offer considerable promise, improvements in master heat production methods and investment casting techniques are being explored by vendors and Pratt & Whitney Aircraft. Based on current data, encouraging ductility advances have been noted. In fact, when thermal stability and mechanical strength (exclusive of ductility) are considered, PWA 659 and PWA 663 are equivalent to PWA 658, and when the expected ductility advances are confirmed by extensive rig and engine testing, these alloys may well surpass the best performance of PWA 658

Although evaluation of all candidate alloys has been discussed largely in terms of creep-rupture, thermal fatigue, and oxidation-erosion resistance, a significant factor concerning the mechanical behavior of these cast nickel-base alloys should be noted. Reversed bending fatigue data for PWA 658 and PWA 659 show high fatigue strength, with notched fatigue strength (10^8 cycles) equivalent to or higher than smooth strength at elevated temperatures. Note that PWA 659 is superior to PWA 658. These notch strengths, which range as high or higher than smooth bar strengths, are most encouraging from a design standpoint. These results are listed in Table F2-5.

TABLE F2-5

FATIGUE PROPERTIES (10^8 CYCLES) FOR

PWA 658 AND PWA 659 ALLOYS

	Smooth		Notched	
Temp.	PWA 658	PWA 659	PWA 658	PWA 659
1200F	38 ksi	41 ksi	32 ksi	46 ksi
1350	38	39	38	39
1500	38	44	38	44

ESTIMATED MINIMUM

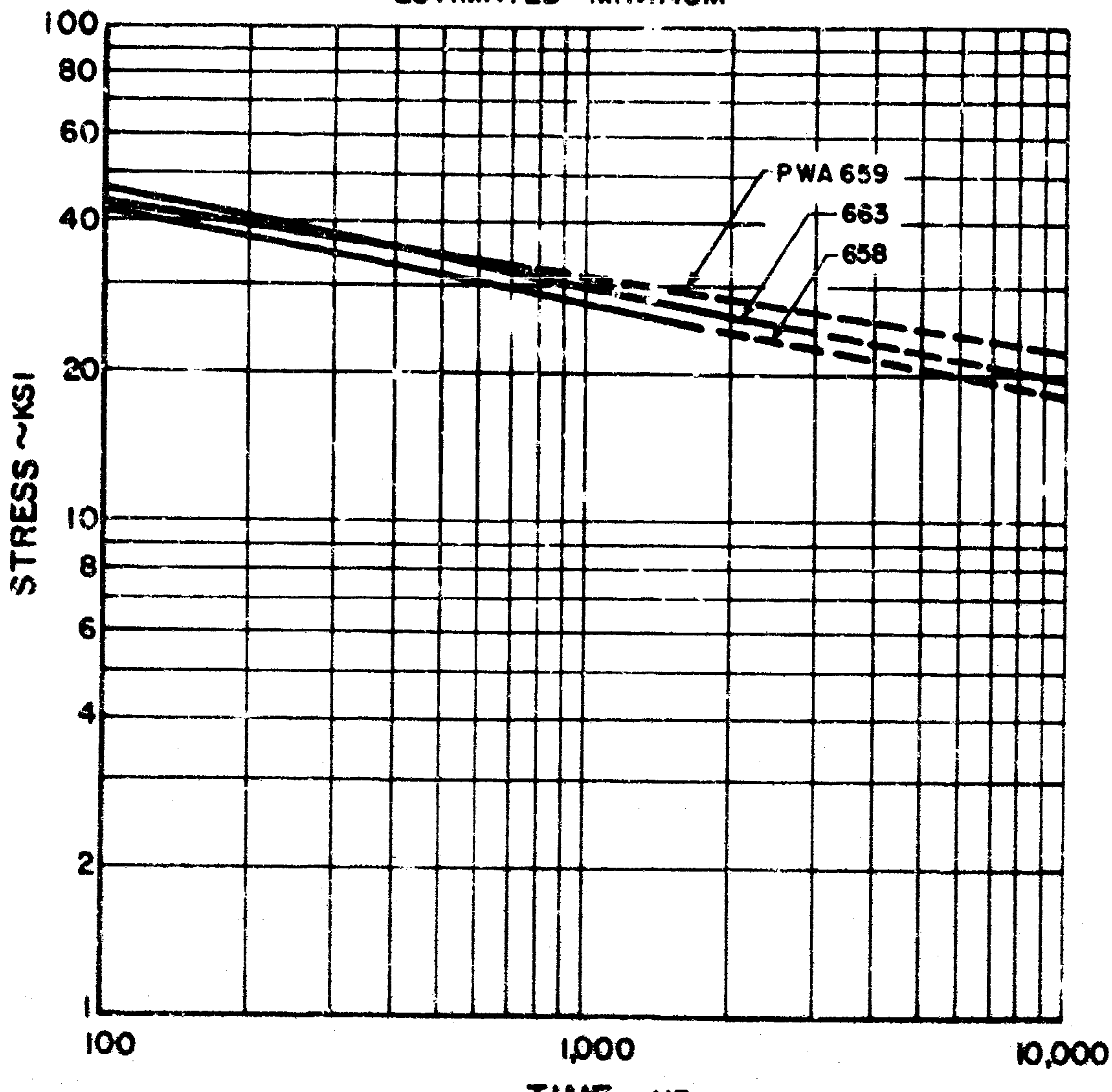

Figure F2-5. 1.0% Creep Strength at 1600°F, PWA 658, PWA 659, PWA 663, Nickel - Base Alloys

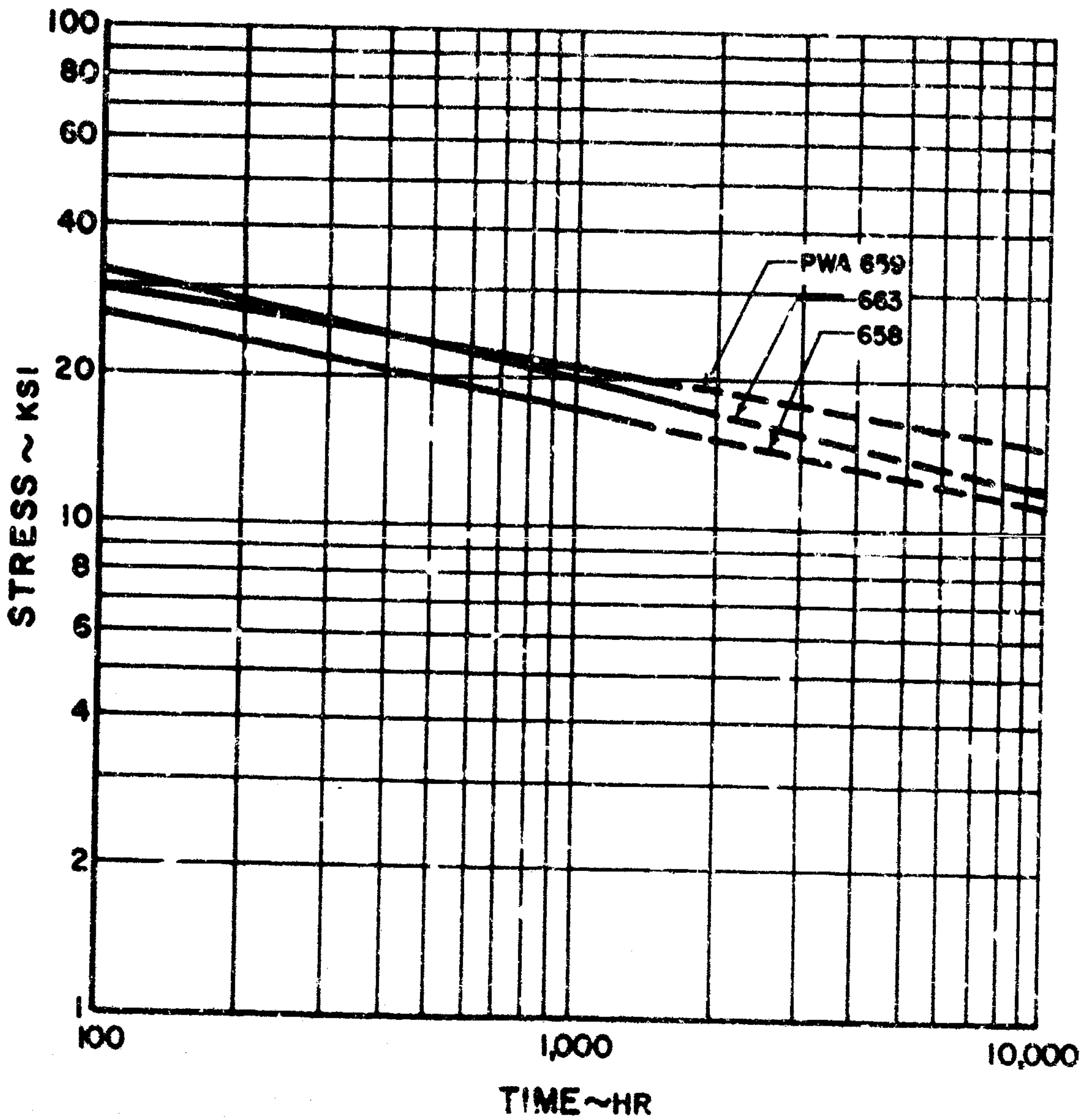

Figure F2-6. 1.0% Creep Strength at 1700°F, PWA 658, PWA 659, PWA 663, Nickel - Base Alloys

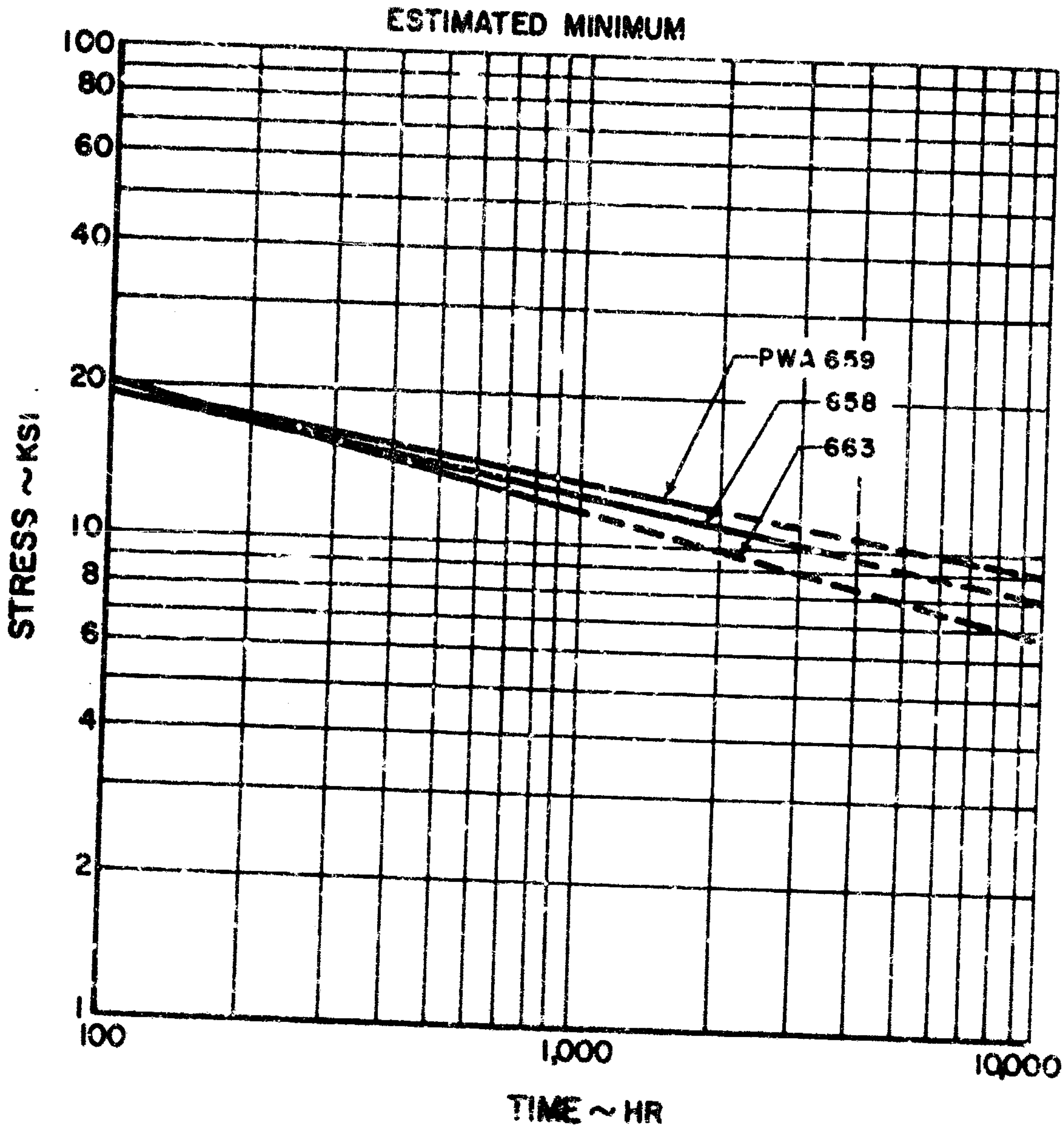

Figure F2-7. 1.0% Creep Strength at 1800°F, PWA 658, PWA 659, PWA 663, Nickel - Base Alloys

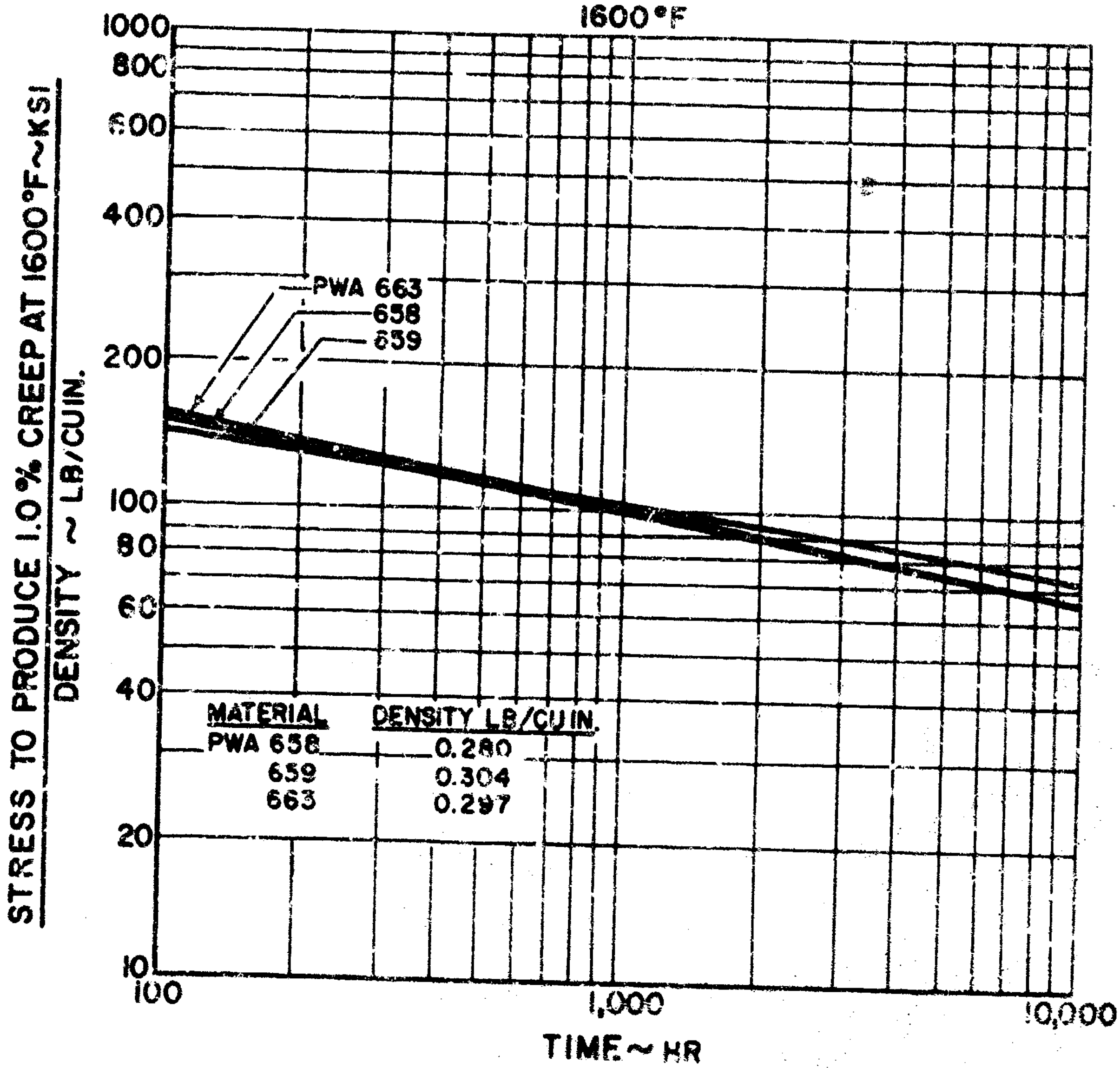

Figure F2-8. Time to 1.0% Creep at 1600°F

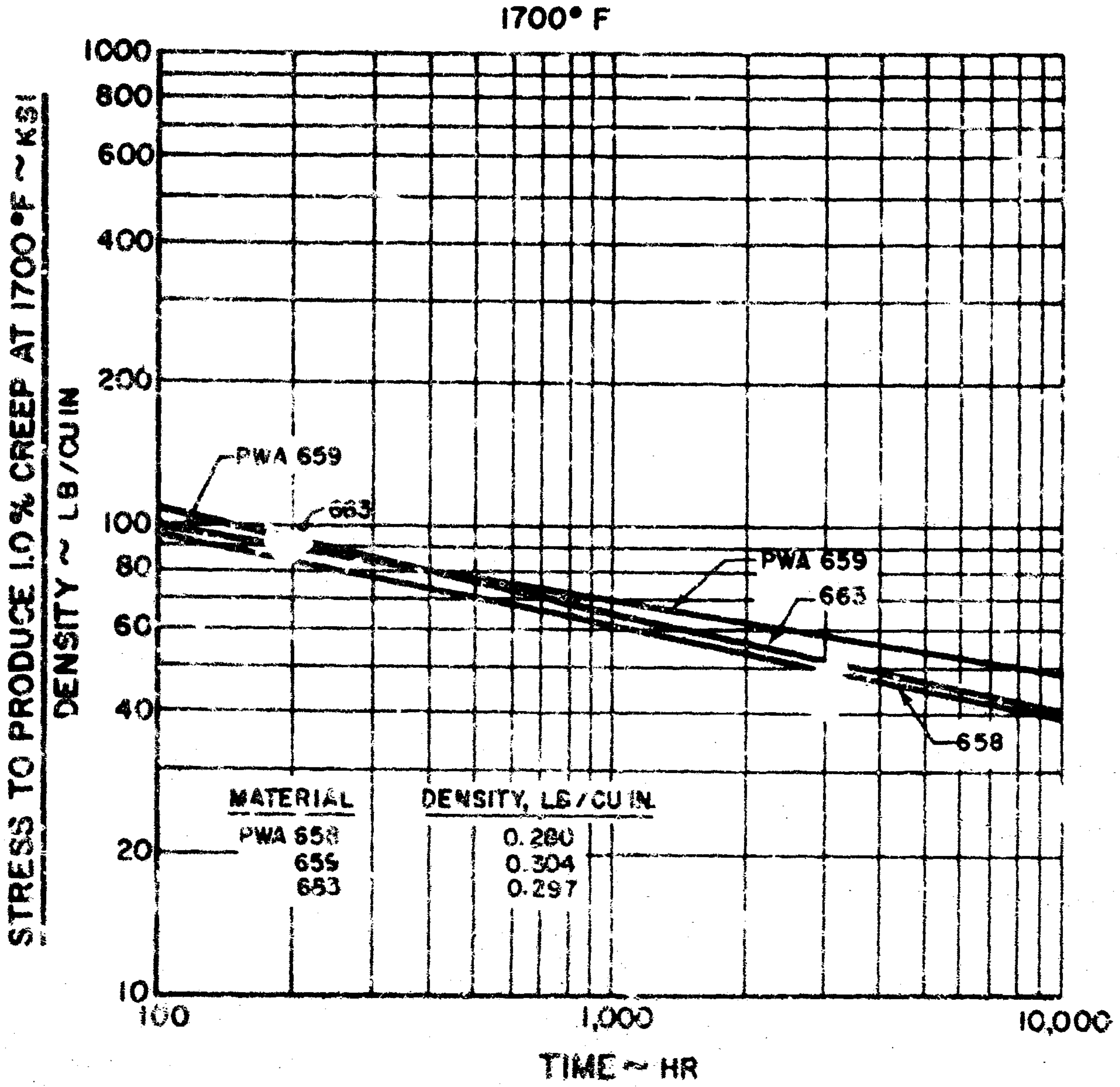

Figure F2-9. Time to 1.0% Creep at 1700° F

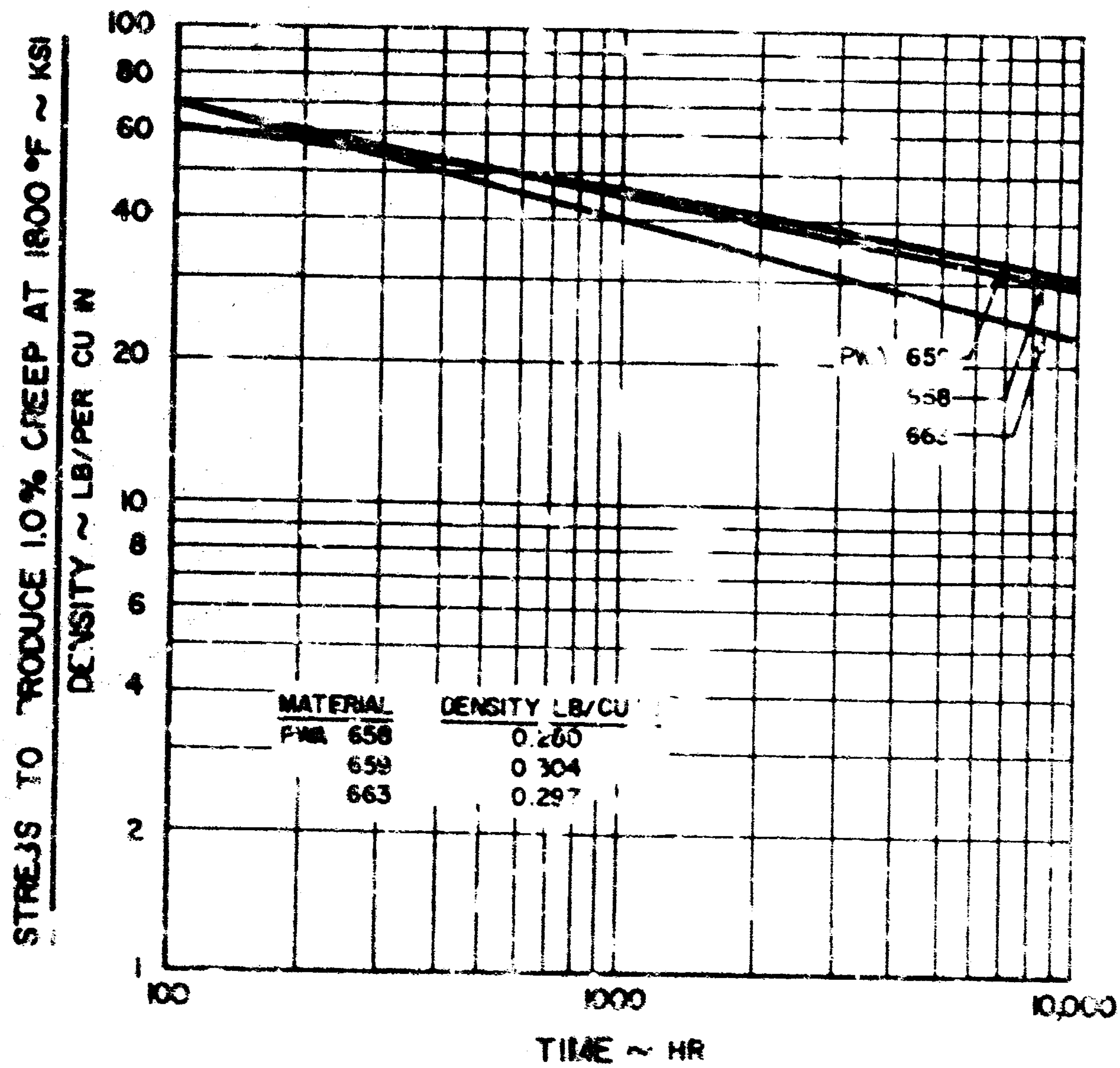

Figure F2-10. Time to 1.0% Creep at 1800°F

2.2 Turbine Vanes

Pratt & Whitney Aircraft has made extensive use of cobalt-base alloys, particularly as precision-cast first stage turbine vanes, because of their excellent resistance to thermal shock, high melting temperature (cobalt has some 70°F superiority over nickel in melting point, 272?°F vs. 2651°F), and good castability. The cobalt alloys gain their strength principally from complex refractory metal carbides, which are difficult to dissolve and diffuse. This carbide strengthening, although effective at high temperatures, is less effective than the strengthening process of the nickel alloys at intermediate temperatures. Thus, cobalt alloys are used more in vane (high temperature) than in blade (intermediate temperature) applications. Pratt & Whitney Aircraft use of cast cobalt alloys includes Stellite 21 (AMS 5385), Stellite 31 (AMS 5382), WI-52 (PWA 653) and SM 302 (PWA 657). The latter two alloys, which use increased amounts of the refractory metals tungsten and tantalum, are significantly stronger than the Stellite 21 and 31 alloys. WI-52 alloy, containing 21Cr-11W-2Fe-1.75Cb-0.45C, has been shown to have the greatest bow resistance of any current cast cobalt base alloy. It does require a suitable protective coating for long time use, and it has been found that a diffused aluminum coating (PWA 45) provides adequate protection for this alloy. The properties and characteristics of the nickel-base superalloys being considered for SST application are described under the turbine blade portion of this section.

The alloys under discussion are fundamentally subject to damaging structural changes dependent upon certain conditions of stress, temperature, and time. Some cobalt-chromium alloys strengthened by refractory metal carbides are susceptible at high temperatures to the formation of a brittle chromium-cobalt intermetallic known as sigma phase. Further, the strengthening carbides under conditions of high heat may coalesce and eventually dissolve, causing loss of strength. The nickel-base alloys strengthened by the Ni_3 (Al, Ti) compound are, of course, also susceptible to loss in strength when overaging (increase in particle size) or dissolving of the hardening constituent occurs at high temperatures. Further, these alloys are to varying degrees susceptible to damage under conditions of thermal cycling and thermal fatigue. Pratt & Whitney Aircraft is very aware of the limitations of the nickel and cobalt systems with regard to long time stability and has, over the years, built up a tremendous amount of experience in this area. Additional information in this area is provided in Section 15 of the Final Contract Report. Materials for the turbine components of Pratt & Whitney Aircraft engines are selected on the basis of meeting long time durability requirements.

PWA 653 (WI-52) has been selected as the first stage vane alloy for the SST engine. This selection was based on the material's good thermal

shock and bow resistance, and the accumulated flight experience in various models of the J52, JT8, JT3, and J75 engines. The alloy requires a protective coating for service above 1700°F but, as stated previously, an established aluminum-base coating has been found to be adequate for this purpose.

PWA 658 (IN 100) has been selected for both the second and third stage vanes in the SST engine based on the excellent performance of this alloy in the J58 engine. The higher stresses in these stages require a stronger alloy than PWA 653. The outstanding properties of PWA 658 alloy, excellent castability and excellent high temperature and thermal fatigue strengths, have been demonstrated in turbine blade applications as described earlier in this section. Stress-rupture acceptance requirements for these two alloys are listed in Table F2-6.

TABLE F2-6

ALLOY STRESS RUPTURE REQUIREMENTS

	Temperature (°F)	Stress (psi)	Life (Hrs. Min.)	Elongation (% Min.)
PWA 653	1800	15,500	23	5
PWA 658	1800	29,000	23	4

These properties and others are controlled by specification. In addition, Pratt & Whitney Aircraft alloy qualification includes stringent rig and experimental engine testing to evaluate bow, thermal fatigue and thermal shock resistance. Average results of such testing are shown in Table F2-7.

All three vane stages will be coated for protection against surface oxidation and corrosion and cooled to decrease metal temperatures to acceptable levels. As indicated previously, PWA 45, a diffusion coating, will be used on WI-52. This alloy-coating system has been used successfully in the J52, JT8, JT3 and J75 engines for millions of hours of commercial and military operation. PWA 47, diffused aluminum-silicon coating, will be used to coat the PWA 658 (IN 100) vanes. Based on maximum expected turbine inlet temperatures and the cooling schemes to be employed, average vane metal temperatures of 1750°F. will be experienced, with maximum temperatures not exceeding 1800°F.

Of several alternate alloys considered for vane use, PWA 659 has been selected as the back-up material to PWA 658 in second and third stage vanes, and PWA 663 for use in all three stages. PWA 663 has demonstrated outstanding thermal shock and thermal fatigue characteristics in both rig and experimental engine tests.

TABLE F2-7

RIG TRAILING EDGE BOW AND THERMAL SHOCK DATA FOR VARIOUS COATED AND UNCOATED NICKEL AND COBALT-BASE ALLOYS

Alloy	Coating	Trailing Edge(1) Bow (Inches)	Trailing Edge Bow(2) In Thermal Shock Bow Test (Inches)	Cycles to Crack(2) In Thermal Shock Bow Test (Cycles)
Nickel-Base				
PWA 658 (IN 100)	None	0.004	0.004	800
PWA 658 (IN 100)	PWA 47	0.003	0.004	900
PWA 659 (SM 200)	None	0.003 - 0.007	0.003 - 0.010	100 - 400
PWA 659 (SM 200)	PWA 47	0.001 - 0.002	0.002 - 0.006	300 - 1200
PWA 663	None	0.002 - 0.010	0.004 - 0.015	200 - 600
PWA 663	PWA 47	0.002 - 0.003	0.003 - 0.004	900 - 1300
Cobalt-Base				
PWA 653 (WI 52)	None	0.005 - 0.007	0.007 - 0.023	100 - 500
PWA 653 (WI 52)	PWA 45	0.004 - 0.008	0.009 - 0.017	500 - 700
PWA 657 (SM 302)	None	0.014 - 0.024	0.029 - 0.072	400 - 600
PWA 657 (SM 302)	PWA 45	0.005	0.025	900

(1) 12 hours at 1950°F and 5000 psi.

(2) 12 hours at 1950°F and 5000 psi + 400 thermal cycles (2100°F - 15 seconds hot, 30 seconds cold)

For future vane and blade consideration new nickel-base alloys recently developed by Pratt & Whitney Aircraft and designated PWA 664, PWA 1401, and PWA 1402 promise thermal fatigue properties far above any existing alloy. The anticipated thermal fatigue life should lead to longer lived and more reliable turbines.

In a more advanced class, the duPont developed dispersion strengthened alloy, TD nickel is a promising vane material. This alloy is attractive because of higher melting point (2650°F), and higher thermal conductivity than conventional superalloys, permitting higher vane operating temperatures and greater resistance to thermal fatigue and shock by minimizing thermal gradients. Uncoated TD nickel sheet metal vanes have shown excellent endurance in 2000°F. rig tests. TD nickel vanes have been engine tested or scheduled for test early in 1965 in J58, TF30, TF33P-7 and JT8D engines. TD nichrome, recently released

by duPont also is receiving a great deal of attention since it has greater oxidation resistance than TD nickel.

Furthermore, a new nickel-base alloy recently developed by Pratt & Whitney Aircraft and designated PWA 664 promises thermal fatigue properties far above any existing alloy. Operating temperatures will necessarily be limited by coating melting point and stability; however, the anticipated thermal fatigue life should lead to longer lived and more reliable turbines.

2.3 Material Descriptions

General descriptions of the chemical composition, mechanical properties, and fabrication characteristics of the materials selected for use in the supersonic engine are presented on the following pages.

AMS 4910 AMS 4926 AMS 4966

GENERAL INFORMATION

SPECIFICATIONS:	AMS 4910	AMS 4926	AMS 4966
FORMS:	Sheet, strip, plate	Bars	Forgings, forging stock
CONDITION:	Annealed	Annealed (Rc 36 max)	Annealed (Rc 36 max)

CMSD.O. DESIGNATION: A-110AT, Ti-5Al-2.5Sn

MELTING PRACTICE: Multiple consumable electrode melted under vacuum

GENERAL DESCRIPTION: Ti-5Al-2.5Sn is an alpha titanium alloy which is not hardenable by heatreatment. Alloy is applicable to compressor components which must be welded and/or which require strengths superior to that of AMS 4901 at temperatures up to 800 F. Tensile strength of alloy is inferior to that of AMS 4928 (Ti -6Al-4V) but its creep strength is superior at temperatures above 800 F. Alloy forges with slightly more difficulty than AMS 4928 and its machinability is comparable to that of the other titanium alloys (similar to austenitic stainless steels). Weldability poses no problem when accomplished with proper techniques. Oxidation resistance is good at temperatures up to 1000 F. Corrosion resistance in general is excellent; however, with adverse combinations of stress, temperature, and halogen media, stress corrosion cracking is possible.

APPLICATIONS: Titanium parts requiring good weldability and strength superior to that of AMS 4901 and AMS 4921 at temperatures up to 800 F. Particularly applicable to compressor components.

CHEMICAL COMPOSITION (Nominal):

C	Al	Sn	Fe	Mn	H	N	Ti
0.15*	5.0	2.5	0.50*	0.30*	0.11	0.07*	remainder

*Maximum

HEATTREATMENT: Not hardenable by heatreatment.
Solution anneal: 1500 F ± 25, air cool.
Vacuum or inert atmosphere required for heatreatment of sheet and finish machined surfaces at temperatures above 1150 F.
Stress-relief: 1150 F for 2 hours in air, air cool.

FORGEABILITY: Good forgeability, but more difficult than AMS 4928 (Ti - 6Al-4V). Recommended forging range is 1900 - 1600 F.

FORMABILITY: Fair to good formability at room temperature; inferior to austenitic stainless steels and AMS 4901 titanium. Annealed sheet (<0.070 in.) is capable of room temperature bend of 105 deg around a diameter which is 6 times its thickness. Maximum formability realized with slow rates of deformation at elevated temperatures (400 - 1200 F).

MACHINABILITY: Somewhat difficult; more difficult than that of commercially pure grades and austenitic stainless steels. Essential requirements for successful machining are: sharp tools, heavy feeds, slow speeds, rigid support, and abundant supply of coolant.

WELDABILITY: Readily weldable by resistance or fusion methods. Fusion welding is done in protective inert gas atmosphere with AMS 4951 (commercially pure titanium) filler metal. Stress-relief at 1150 F for 2 hours in air required for large or complex fusion weldments.

BRAZEABILITY: Not readily brazeable. Limited experimental brazing has produced ductile joints with pure silver brazing metal. For specific applications consult Design Metallurgy.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General corrosion resistance is excellent. Subject to stress corrosion failure when exposed under stress to halogen-containing atmospheres at temperatures above 500 F.

OXIDATION RESISTANCE: Resists oxidation at temperatures up to approximately 1000 F. Extended exposure at 1000 F and higher results in loss of ductility and fatigue strength due to diffusion of oxygen.

PWA 1202

GENERAL INFORMATION

SPECIFICATION: PWA 1202, PWA 1204

FORM: Bars, forgings, forging stock

CONDITION: Bars and forgings: Solution and stabilization annealed - RC 39 maximum
Forging stock: As ordered by forger

COMMON DESIGNATION: Ti-8Al-1Mo-1V

MELTING PRACTICE: Multiple consumable electrode melted under vacuum

GENERAL DESCRIPTION: Ti-8Al-1Mo-1V is an alpha-lean beta titanium alloy which is used in the duplex annealed condition. Alloy is particularly applicable to jet engine compressor components which require good strength and thermal stability within the temperature range 500 - 1000 F. Alloy is superior in strength to annealed AMS 4928 (Ti-6Al-4V) alpha-beta alloy particularly at temperatures above 600 F. Metallurgical and surface stability are good up to approximately 1000 F. Alloy forges with slightly more difficulty than AMS 4928 and its machinability is comparable to that of the other titanium alloys (similar to austenitic stainless steels). Weldability in general is comparable to that of AMS 4910; however, where joint restraints are high, welding may be more difficult. Oxidation and corrosion resistance are similar to that of AMS 4910 (A-110AT).

APPLICATIONS: Titanium parts requiring superior tensile yield and creep strengths within the temperature range of 500 - 900 F. Used primarily for compressor blades and discs.

CHEMICAL COMPOSITION (Nominal):

C	Al	Mo	V	Fe	O	N	H	Ti
0.08*	8.0	1.0	1.0	0.30*	0.15*	0.05* (500 ppm)	0.015* (150 ppm)	remainder

*Maximum

HEATTREATMENT:

Solution anneal: 1625 - [illegible]75 F for 1 hr, air cool
Stabilize anneal: 1035 - 1115 F for 8 hr (min.), air cool
Normal heatreatment is a duplex treatment which incorporates both solution and stabilizing anneals. Solution annealing within 1775 - 1975 F range enhances elevated temperature strength and room temperature notch strengths at the expense of some loss of room temperature tensile ductility.

FORGEABILITY: Good forgeability, slightly more difficult than AMS 4928 (Ti-6Al-4V). Recommended forging range is 1880 - 1650 F.

MACHINABILITY: Somewhat difficult due to high rate of work hardening. Machining accomplished with same general techniques employed for austenitic stainless steels, but with slightly more difficulty.

WELDABILITY: Ductile welds with good strengths are obtainable by resistance or fusion methods generally used for AMS 4910 (A-110AT) alpha type titanium alloy. For stress relieving heat treatments required after fusion welding large or complex assemblies, consult Design Metallurgy. For a given weldment involving joints of moderate to high restraint, alloy may be more difficult to weld than AMS 4910.

BRAZEABILITY: Preliminary Materials Development Laboratory data indicates that successful joints can be produced with Ag base brazing alloy. Brazeability in general should be similar to that of A-110[illegible]

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General corrosion resistance is excellent. Subject to stress-corrosion cracking when exposed under stress to halogen containing atmospheres at temperatures above [illegible] F.

OXIDATION RESISTANCE: Resists oxidation at temperatures up to approximately 1000 F. Extended periods of exposure at higher temperatures results in loss of ductility and deterioration of all properties in general.

PWA 1203

GENERAL INFORMATION

SPECIFICATION: PWA 1203

COMMON DESIGNATION: Ti-5Al-5Zr-5Sn

FORM: Bars, forgings, forging stock, sheet

CONDITION: Annealed

MELTING PRACTICE: Multiple consumable electrode melted under vacuum

GENERAL DESCRIPTION: Ti-5Al-5Zr-5Sn is an alpha titanium alloy which is not hardenable by heatreatment. Alloy is applicable to jet engine compressor components which require good strength and stability within 800 to 1000 F range. Compared with PWA 1202 (Ti-8Al-1Mo-1V), alloy has lower elevated temperature tensile properties and higher creep resistance above 800 F, and has comparably good stability up to 1000 F. Forgeability of alloy is similar to that of Ti-7Al-12Zr but considerably poorer than that of PWA 1202. Weldability is roughly comparable to PWA 1202 and slightly more difficult than A-110AT for weldments with high weld joint restraint. Oxidation and corrosion resistance are comparable to those of A-110AT and PWA 1202.

APPLICATIONS: Compressor components requiring creep resistance superior to that of AMS 4966 (A-110AT) and PWA 1202 (Ti-8Al-1Mo-1V) within 800 - 1000 F temperature range.

CHEMICAL COMPOSITION (Nominal):

C	Al	Zr	Sn	Fe	O	N	H	Ti
0.08*	5.0	5.0	5.0	0.15*	0.10*	0.05* (500 ppm)	0.013* (130 ppm)	remainder

*Maximum

HEATTREATMENT: Not hardenable by heatreatment. Generally used in single or duplex annealed condition. Best heatreatment to date for optimum combination of tensile, creep, and stability has been: 1650 F/4 hr/air cool.

FORGEABILITY: Difficult. Similar to Ti-7Al-12Zr titanium alloy, but considerably more difficult than PWA 1202 (Ti-8Al-1Mo-1V) and AMS 4928 (Ti-6Al-4V). Usually forged between 1625 F and 1700 F.

MACHINABILITY: Somewhat difficult due to high rate of work hardening. Comparable to other titanium alloys and slightly more difficult than the austenitic stainless steels.

WELDABILITY: No PWA experience to date. Published literature indicates that ductile welds with good strengths are possible by techniques used for A-110AT. For a given weldment involving joints of moderate to high restraint, alloy may be more difficult to weld than A-110AT or Ti-8Al-1Mo-1V. For stress relieving heatreatments required for large or complex weldments, consult Design Metallurgy.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General corrosion resistance is excellent. Subject to stress corrosion cracking when exposed under stress to halogen containing atmospheres at temperatures above 500 F.

OXIDATION RESISTANCE: Comparable to PWA 1202.

AMS 5613 AMS 5504 AMS 5591

GENERAL INFORMATION

SPECIFICATION: AMS 5613 | AMS 5504 | AMS 5591

AVAILABLE FORMS: Bars, forgings | Sheet, strip, plate | Seamless tubing

CONDITION: Bar: Hot and cold finished, Bhn 241 max
Forgings: As ordered
Sheet: Annealed

COMMON DESIGNATION: AISI Type 410, SAE 51410

MELTING PRACTICE: Generally air melted in electric furnace. Vacuum melted and vacuum degassed materials are available for special applications.

GENERAL DESCRIPTION: AISI Type 410 is a martensitic, corrosion resistant steel which is heatreatable over hardness range of Rb 90 - Rc 46. Stress-rupture and creep strengths of alloy are inferior to those of Greek Ascoloy (AMS 5616, AMS 5508) when heatreated to same hardness. Yield strength of alloy is comparable to that of Greek Ascoloy (same hardness level) at temperatures up to approximately 800 F, but inferior at higher temperatures. Forgeability, machinability, and weldability of alloy are slightly superior to Greek Ascoloy. General corrosion resistance of alloy is superior to that of low alloy steels and comparable to Greek Ascoloy. When tempered within 700 - 1100 F range, alloy is susceptible to stress corrosion cracking. Oxidation resistance of alloy is good up to approximately 1000 F.

APPLICATIONS: A wide variety of structural parts requiring moderate to high strength and rust resistance at temperatures up to approximately 950 F and which might require welding or brazing. Also used where low expansion is desirable.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Ni	Mo	Mn	Si	Al	Cu	Sn	P	S	Fe
0.15*	12.5	0.75*	0.5*	1.0*	1.0*	0.05*	0.5*	0.05*	0.04*	0.03*	remainder

*Maximum

HEATTREATMENT:
Austenitize: 1750 - 1850 F for ¼ - ¾ hr, air cool or oil quench
Temper range: 900 - 1250 F for 2 hr, air cool (See "Hardness vs. Tempering Temperature" curve for specific hardness levels and temperature)
Process anneal: 1200 - 1400 F for 1 - 2 hr, air cool; typical hardness - Bhn 185
Full anneal: 1550 - 1650 F (1 hr per section inch), furnace cool to 900 F, air cool; typical hardness - Bhn 155

FORGEABILITY: Readily forged, more easily than AMS 5616 hardenable, corrosion resistant steel. Usual forging temperature range is 2150 - 1500 F.

FORMABILITY: Fair. More difficult to form in annealed condition than the austenitic stainless steels, but more easily formed than AMS 5508 hardenable, corrosion resistant steel. "In process" anneals may be necessary depending upon degree and nature of forming operation. Severe deforming operations should be followed by stress relief or anneal.

MACHINABILITY: Fair to good. Slightly better than AMS 5616 hardenable, corrosion resistant steel and the austenitic stainless steels. Optimum condition for machining is hardened and tempered, or annealed and cold worked to hardness of Bhn 200 - 260.

WELDABILITY: Fair to good. Can be fusion or resistance welded with less difficulty than AMS 5508 hardenable, corrosion resistant steel. High strength assemblies are usually welded in the annealed condition, and subsequently austenitized and tempered. Fusion welding is usually done with filler metal of parent metal chemistry; use of austenitic type filler metals is permitted when hardened details are to be joined and/or welded joints have low strength requirements.

GENERAL INFORMATION (cont.)

BRAZABILITY: Readily brazed by all methods. Assemblies gold-nickel brazed per PWA 12 or silver brazed per AMS 2666 may be hardened in the brazing cycle. Copper brazing per AMS 2671 should be followed by separate hardening and tempering operations. Stress relief or temper heatreatment is required after AMS 2666 silver brazing and gold-nickel brazing; no heatreatment necessary after AMS 2665 silver brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General corrosion resistance of alloy is superior to that of low alloy steels but is inferior to that of austenitic stainless steels. Corrosion resistance is reduced by exposures to temperatures above 800 F; hardened material has best corrosion resistance when heatreated per PWA 12. Alloy, like AMS 5616 (Greek Ascoloy), is susceptible to stress corrosion cracking when tempered within 700 - 1100 F range. For tempering temperatures up to 700 F, AMS 5613 and AMS 5616 both have equally good stress corrosion resistance; at equal strength levels produced by tempering above 1000 F, AMS 5613 is somewhat inferior to AMS 5616.

OXIDATION RESISTANCE: Slightly inferior to AMS 5616, hardenable, corrosion resistant steel and substantially superior to low alloy steels. Resists oxidation at temperatures up to approximately 1000 F.

AMS 5616 AMS 5508

GENERAL INFORMATION

SPECIFICATION: AMS 5616 — AMS 5508

AVAILABLE FORMS: Bars, forgings — Sheet, strip, plate

CONDITION: Bar: Annealed; Bhn 311 max
Forgings: As ordered
Sheet: Annealed

COMMON DESIGNATION: Greek Ascoloy, Uniloy 1415 NW

MELTING PRACTICE: Generally air melted in electric furnace; however, vacuum melted and vacuum degassed materials are available.

GENERAL DESCRIPTION: AMS 5616 is a martensitic, corrosion resistant steel whose strength at elevated temperatures is enhanced by additions of nickel and tungsten. Alloy is heatreatable over hardness range of Rc 28 - 50. Stress-rupture and creep strengths of alloy are superior to those of AMS 5613 (AISI Type 410 steel) but inferior to those of AMS 5735 (A-286) and AMS 6304 (low alloy steel). Forgeability, machinability, and weldability of alloy are slightly inferior to AMS 5613. General corrosion resistance of alloy is superior to that of low alloy steels. Material tempered within 700 - 1100 F range is susceptible to stress corrosion cracking. Oxidation resistance of alloy is good up to approximately 1000 F.

APPLICATIONS: Parts requiring creep strength and tempering resistance superior to that of AMS 5613. Used primarily for compressor blades and vanes, turbine discs, nuts, bolts, and miscellaneous structural parts exposed to temperatures up to 1000 F.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Ni	W	Mo	Mn	Si	P	S	Al	Cu	Sn	Fe
0.17%	13.0	2.0	3.0	0.5*	0.5*	0.5*	0.04*	0.03*	0.15*	0.5*	0.05*	remainder

*Maximum

HEATREATMENT:

Austenitize: 1750 - 1850 F for ½ hr, air or oil quench. Through hardening attained in section sizes up to approximately 3.0 inches by either air cool or oil quench. Larger sizes require oil quench for maximum hardness.

Temper range: 450 - 600 F and 1000 - 1250 F for 2 hr, air cool (See "Hardness vs. Tempering Temperature" curve for specific hardness levels and temperatures). Double temper or cold treatment recommended for parts hardened to Rc 45 - 50.

Process anneal: 1300 F for 1 - 2 hr, air cool; resulting hardness Bhn [illegible]70.

Full anneal: 1450 - 1500 F (1 hr per section inch), furnace cool at 30 F/hr to 800 F, air cool; resulting hardness Bhn [illegible] - 277.

FORGEABILITY: Readily forged; slightly more difficult than AMS 5613 (AISI Type 410). Usual forging temperature range 2100 - 1750 F.

FORMABILITY: Fair. More difficult to form in annealed condition than annealed AMS 5504 (AISI Type 410) and austenitic stainless steels. Does not work harden as rapidly as austenitic stainless steels; however, intermittent process anneals may be necessary depending upon degree and nature of forming operation. Full anneal recommended after severe deformations.

MACHINABILITY: Fair. Similar to the austenitic stainless steels but slightly inferior to AMS 5613. Fully annealed condition is optimum for machining.

WELDABILITY: Fair. Can be fusion and resistance welded but with more difficulty than AMS 5504 (AISI Type 410) due to its higher hardenability. Air hardening characteristics of alloy necessitate post weld stress relief within reasonably short time after welding. Weldments requiring high strength should be joined in annealed condition, and subsequently austenitized and tempered. Filler metal of parent metal composition is recommended for high strength weldments.

AMS 5616 AMS 5508

GENERAL INFORMATION (cont.)

BRAZEABILITY: Readily brazed by all methods. Assemblies gold-nickel brazed per PWA 19 or silver brazed per AMS 2666 may be hardened in the brazing cycle. Copper brazing per AMS 2671 should be followed by separate hardening and tempering operations. Stress relief or temper heatreatment is required after AMS 2666 silver brazing and gold-nickel brazing; no heatreatment necessary after AMS 2665 silver brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General corrosion resistance of alloy is superior to that of low alloy steels but is inferior to that of austenitic stainless steels. Corrosion resistance is reduced by exposures to temperatures above 800 F; hardened material has best corrosion resistance when heatreated per PWA 19. Alloy, like AMS 5613 (AISI Type 410), is susceptible to stress corrosion cracking when tempered within 700 - 1100 F range. For tempering temperatures up to 700 F, AMS 5613 and AMS 5616 both have equally good stress corrosion resistance; at equal strength levels produced by tempering above 1000 F, AMS 5616 is somewhat better than AMS 5613.

OXIDATION RESISTANCE: Slightly better than AISI Type 410 and substantially superior to low alloy steels. Resists oxidation at temperatures up to approximately 1000 F.

AMS 5510 AMS 5570 AMS 5576 AMS 5645

GENERAL INFORMATION

SPECIFICATIONS:	AMS 5510	AMS 5570	AMS 5576	AMS 5645
FORMS:	Sheet, plate, strip	Seamless tubing	Welded tubing	Bars, forgings, mechanical tubing

CONDITION: Solution heatreated

COMMON DESIGNATIONS: Type 321 Stainless Steel; AISI 321; SAE 30321; Ti stabilized 18-8 Stainless Steel

MELTING PRACTICE: Electric furnace, air melted

GENERAL DESCRIPTION: AISI Type 321 is an 18-8 type austenitic stainless steel with titanium additions which stabilize this alloy against intergranular carbide precipitation and subsequent corrosive attack. Alloy is not hardenable by heatreatment and is used in the solution heatreated condition for maximum corrosion resistance and ductility. Alloy is within same general strength category as AISI 310, 316, and 347 austenitic stainless steels. Furnace brazing requires special consideration but otherwise fabrication is readily achieved by procedures and techniques common to other austenitic stainless steels. Resists oxidation at temperatures up to approximately 1600 F and is like AISI 316 and 347 in this respect, but is inferior to AISI 310 and Inconel.

APPLICATIONS: Parts requiring oxidation and corrosion resistance at temperatures up to approximately 1500 F; useful only where operating stresses are low. For assemblies fabricated by brazing or welding.

CHEMICAL COMPOSITION (Nominal)

C	Cr	Ni	Ti	Mo	Mn	Si	Cu	P	S	Fe
0.08*	18.0	10.0	0.7*	0.5*	2.0*	0.7*	0.5*	.04*	.03*	remainder

*Maximum

HEATTREATMENT: Not hardenable through heatreatment.
Solution (full anneal): 1750 - 1950 F for ½ to 1 hour per section inch; cool to below 800 F in less than 3 minutes.
Solution heatreat sheet at 1975 F for 7 - 10 minutes after severe forming operations.
Stress-relieve complex fusion weldments at 1500 F for 1 hour.

FORGEABILITY: Readily forged. Usually forged within 2300 - 1700 F range.

FORMABILITY: Sheet can be bent 180 deg around a diameter equal to its thickness. Excellent drawing and spinning characteristics. Solution heatreat at 1975 F for 7 - 10 minutes after severe forming operations.

MACHINABILITY: Somewhat difficult due to high rate of work-hardening. Slightly superior to that of Inconel or Hastelloy X nickel-base alloys. Requirements: rigidly supported work; accurately ground, highly sharpened, rigidly supported tools; positive, uniform feed; positive chip removal; adequate cooling with sulphurized-base oils. Non-magnetic.

WELDABILITY: Readily fusion or resistance welded. Filler metal of AISI 347 composition used for fusion welding. Large or complex weldments require stress-relief at 1500 F for 1 hour. Minor fusion weldments and resistance weldments need not be stress-relieved.

BRAZEABILITY: Readily brazed with silver, copper, nickel, and gold-nickel. Furnace brazing in hydrogen atmosphere not feasible unless parts to be brazed are nickel plated. No stress-relief required after brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Excellent corrosion resistance in gas turbine engine atmospheres at temperatures up to approximately [illegible] F. "Stabilized" by titanium content against intergranular chromium carbide precipitation in the range 800 - 1650 F, thus corrosion resistance of parts remains good after processing or operation in that range.

OXIDATION RESISTANCE: Good at temperatures up to approximately 1600 F. Comparable to AISI 316 and 347 austenitic stainless steels, but inferior to AISI 310 stainless steel and Inconel nickel-base alloy.

AMS 5512 AMS 5571
AMS 5575 AMS 5646 PWA 770

GENERAL INFORMATION

SPECIFICATIONS:	AMS 5512	AMS 5571	AMS 5575, PWA 770	AMS 5646
FORMS:	Sheet, strip, plate	Seamless tubing	Welded tubing	Bars, forgings, mechanical tubing

CONDITION: Solution heatreated

COMMON DESIGNATIONS: Type 347 Stainless Steel; AISI 347; SAE 30347; Columbium Stabilized 18-8 Stainless Steel

MELTING PRACTICE: Electric furnace air melt. Induction and consumable electrode vacuum melted.

GENERAL DESCRIPTION: AISI Type 347 is an 18-8 type austenitic stainless steel in which addition of columbium stabilizes material against intergranular carbide precipitation and subsequent corrosive attack. Alloy is not hardenable by heatreatment and is used in the solution heatreated condition for maximum corrosion resistance and ductility. Alloy is within same general strength category as AISI 316, 321 and 310 austenitic stainless steels. Readily fabricable by procedures and techniques common to other austenitic stainless steels. Resists oxidation at temperatures up to approximately 1600 F and is like AISI 316 and 321 in this respect, but is inferior to AISI 310 and Inconel.

APPLICATIONS: For corrosion and oxidation resistant parts operating under low stresses at temperatures to 1500 F, and for assemblies fabricated by brazing or welding.

CHEMICAL COMPOSITION (nominal):

C	Cr	Ni	Cb	Mn	Si	Mo	Cu	P	S	Fe
0.08*	18.5	11.0	1.1*	2.0*	0.75	0.5*	0.5*	.04*	.03*	remainder

*maximum

HEATTREATMENT: Not hardenable through heatreatment.
Solution: 1800 - 1950 F for ½ - 1 hr per section inch; cool to below 800 F in less than 3 minutes.
Solution heatreat sheet at 1925 F for 7 - 10 minutes after severe forming operations.
Stress-relieve complex fusion weldments at 1200 F for 1 hour.

FORGEABILITY: Readily forged. Usually forged between 2300 F and 1700 F.

FORMABILITY: Sheet can be bent 180 deg around a diameter equal to its thickness. Excellent drawing and spinning characteristics. Solution heatreat at 1925 F for 7 - 10 minutes after severe forming operations.

MACHINABILITY: Comparable to that of AISI type 321 and the other austenitic stainless steels and slightly superior to Inconel and Hastelloy X nickel base alloys. See page 3.1. Non-magnetic.

WELDABILITY: Readily fusion and resistance welded. Filler metal of parent metal composition used for fusion welding. Large or complex weldments should be stress-relieved at 1200 F for 1 hour. Minor fusion weldments and resistance weldments need not be stress-relieved.

BRAZEABILITY: Readily brazed with silver, copper, nickel, and gold-nickel. No stress-relief required after brazing. This material (AISI 347) is recommended for use where furnace brazing is required.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Excellent corrosion resistance in gas turbine engine atmospheres at temperatures up to approximately 1600 F. "Stabilized" by columbium content against intergranular chromium carbide precipitation in the range 800 - 1650 F, thus corrosion resistance of parts remains good after processing or operation in that range.

OXIDATION RESISTANCE: Good at temperatures up to 1600 F. Comparable to AISI 316 and 321 austenitic stainless steels but inferior to Inconel and AISI 310.

AMS 5540 AMS 5580 AMS 5665 AMS 5687
PWA 1060

GENERAL INFORMATION

SPECIFICATION:	AMS 5540	AMS 5580 PWA 1060	AMS 5665	AMS 5687
FORM:	Sheet, strip, plate	Seamless tubing	Bars, forgings, welded rings	Wire
CONDITION:	Annealed	Annealed	Annealed, hot finished	Annealed

COMMON DESIGNATION: Inconel

MELTING PRACTICE: Induction furnace, air melted

GENERAL DESCRIPTION: Inconel is a nickel base alloy richly alloyed primarily with chromium. Alloy is non-hardenable by heatreatment and is used in solution heatreated (annealed) condition. Yield strength of alloy is retained at temperatures up to about 1100 F. Minimum yield strengths at 1000 F and 1600 F are 23.0 ksi and 6.0 ksi, respectively. Minimum 100 hr stress-rupture and 150 hr, 0.5% creep strengths of alloy at 1600 F are 4.5 ksi and 2.2 ksi, respectively. Yield and creep-rupture strengths of alloy are comparable to those of austenitic stainless steels and inferior to those of Hastelloy X and L-605. Fabricability of alloy, in general, is similar to that of the austenitic stainless steels. Oxidation resistance of alloy is superior to that of the austenitic stainless steels and L-605, but slightly inferior to that of Hastelloy X. Corrosion resistance is excellent.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Fe	Co	Mn	Si	Cu	S	Ni	Ti	Al	Al + Ti
0.15% max	15.5	8.0	1.5 max	1.0 max	0.5 max	0.5 max	0.015 max	remainder	0.3 max*	0.3 max*	0.4 max*

*Applicable to PWA 1060 only.

HEATREATMENT: Anneal (Solution): 1925 F ± 25 for ½ to 1 hr - air cool, forgings
1800 F for 10 - 15 min - air cool, sheet
Stress relief: 1600 - 1700 F for 1 hr, air cool
Optimum heatreatment for good formability is 1900 F for 10 - 15 minutes followed by air cool or [illegible] for several seconds. Coarse grain size produced by excessive times at 1900 F [illegible] above results in decrease in yield strength and ductility. All heatreating of alloy should be performed in sulfur-free atmospheres. Alloy resists bright annealing, nitriding, and carburizing atmospheres.

FORGEABILITY: Usually forged in temperature range of 2150 - 1750 F.

FORMABILITY: Good, superior to Hastelloy X and austenitic stainless steels. High rate of work hardening requires intermediate anneals for severely formed parts.

MACHINABILITY: Difficult, similar to Hastelloy X and more difficult than standard austenitic stainless steels. Sulfur bearing cutting fluids must be removed prior to heatreatment or high temperature service.

WELDABILITY: Readily welded in solution heatreated condition by fusion and resistance methods. Filler metal of parent metal composition used for fusion welds. Complex fusion weldments require post-weld stress relief.

BRAZEABILITY: Can be silver, copper, and gold-nickel brazed without post-braze stress relief. Furnace brazed assemblies require use of PWA 1060 (furnace brazing quality material). Brazed details should be in solution heatreated condition or stress relieved prior to brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Excellent.

OXIDATION RESISTANCE: Excellent in sulfur free atmospheres at temperatures up to 2000 F and in sulfur atmospheres up to 1800 F. Superior to austenitic stainless steels and L-605 but slightly inferior to Hastelloy X.

AMS 5536 AMS 5754

GENERAL INFORMATION

SPECIFICATION: AMS 5536 AMS 5754

AVAILABLE FORMS: Sheet Bars, forgings

CONDITION: Solution heatreated

COMMON DESIGNATIONS: Hastelloy X, Hastelloy Alloy X

MELTING PRACTICE: Electric furnace, air melted

GENERAL DESCRIPTION: AMS 5536 is a nickel base alloy richly alloyed primarily with chromium. Alloy is essentially non-hardenable by heatreatment and is normally used in solution heatreated condition. Precipitation occurs in alloy during long exposures within temperature range of 1200 - 1800 F; however, subsequent increase in hardness and decrease in ductility are tolerable in so far as performance in service is concerned. Minimum yield strengths range from 37.0 ksi at 600 F to 10.0 ksi at 1800 F. Minimum 100 hr stress-rupture strength and 100 hr, 0.5% creep strength at 1500 F are 11.0 ksi and 5.0 ksi, respectively. Yield and rupture strengths of alloy are superior to those of AMS 5540 (Inconel), AMS 5510 (AISI 321), and AMS 5512 (AISI 347) but inferior to those of AMS 5537 (L-605). Alloy forges, forms, machines, and welds with slightly more difficulty than austenitic stainless steels commonly used at PWA. Oxidation resistance of alloy is outstanding at temperatures up to 2200 F and is superior to that of AMS 5510, AMS 5540, and AMS 5537. Corrosion resistance of alloy is excellent.

APPLICATIONS: Parts requiring moderate strength, and excellent oxidation and corrosion resistance within temperature range of 1400 - 2000 F. Used primarily for burner liner parts, turbine seals, turbine exhaust weldments, and afterburner parts.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	Mo	W	Fe	Mn	Si	P	S	Ni
0.10%	22.0	1.5	9.0	0.6	18.5	1.0*	1.0*	0.04*	0.03*	remainder

*Maximum

HEATREATMENT: Solution: 2150 F ± 25 - 1 hr per section inch - water quench or rapid air cool. Resulting hardness Rb 85 - 100.
Anneal (Process or full): Same as solution heatreatment.
Furnace atmospheres for annealing or heating for hot working should be free from sulfur.

FORGEABILITY: Fair. Usually forged in temperature range of 2200 - 1800 F. More readily forged than L-605.

FORMABILITY: Good. Slightly more difficult to form than austenitic stainless steels. Depending upon degree and nature of forming operation, several in-process anneals may be necessary due to high rate of work hardening.

MACHINABILITY: Difficult. Slightly more difficult to machine than austenitic stainless steels and Inconel. All traces of sulfur bearing cutting fluid must be removed prior to heatreatment or high temperature service.

WELDABILITY: Can be fusion and resistance welded. Some thickness and material combinations offer difficulty in resistance welding. Filler metal of parent metal composition used for fusion welding.

BRAZEABILITY: Readily brazed by all methods (silver, copper, gold-nickel). Cold formed details must be annealed prior to brazing. Post brazing stress relief not essential

CHEMICAL PROPERTIES

OXIDATION RESISTANCE: Excellent resistance to oxidizing atmospheres at temperatures up to 2200 F. Resistance to reducing and inert media at temperatures up to 2150 F is also outstanding. Superior to austenitic stainless steels, Inconel, and L-605.

CORROSION RESISTANCE: Excellent.

AMS 5542 AMS 5582 AMS 5667 AMS 5668 AMS 5698 AMS 5699 PWA 1031 PWA 1063

GENERAL INFORMATION

SPECIFICATION:	FORM:	CONDITION:
AMS 5542	Sheet, strip, plate	Annealed
PWA 1031	Strip (vac. melted)	Annealed
AMS 5667	Bars, forgings, rings, forging stock	Equalized
AMS 5668	Bars, forgings, forging stock	Solution, stabilization, and precipitation heatreated
AMS 5582	Seamless tubing	Annealed
PWA 1063	Welded tubing	Annealed
AMS 5698	Wire	Cold reduced 15 - 20%
AMS 5699	Wire	Cold reduced 50 - 65%

COMMON DESIGNATION: Inconel X, Inconel alloy X-750

MELTING PRACTICE: Primarily induction melted in air; PWA 1031 is induction or consumable electrode melted under vacuum.

GENERAL DESCRIPTION: Inconel X is a nickel-base alloy which has useful strengths at temperatures up to 1350 F or 1500 F, depending upon its heatreated condition, and has good oxidation and corrosion resistance in gas turbine engine atmospheres up to 1800 F. Like Waspaloy, subject alloy is capable of a wide range of mechanical properties which can be optimized by appropriate heatreatment for specific operating conditions. In general, tensile and creep-rupture strengths with 1300 F age fall between those of AMS 5525 (A-286) and PWA 1033 (Inconel 718) at temperatures up to 1350 - 1400 F. Alloy becomes notch sensitive in stress-rupture after prolonged exposures at 1100 - 1350 F. Alloy is weldable but with considerable difficulty. Machining, forging, and forming characteristics of Inconel X are similar to those of Incoloy 901 (PWA 1003) and Inconel 718 (PWA 1010, PWA 1033).

APPLICATIONS: Parts requiring good strength at temperatures up to 1350 F or 1500 F plus good oxidation and corrosion resistance. Used primarily for non-rotating structural parts, non-structural parts (springs, seals), and tube assemblies.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Ti	Al	Cb + Ta	Fe	Mn	Si	S	Cu	Ni
.08%*	15.5	2.5	.7	1.0	7.0	1.0*	.5*	.01*	.5*	remainder

*Maximum

HEATREATMENT: Heatreatable by various combinations of solution and precipitation heatreatments to comply with particular application and/or fabrication requirements. In general, for parts used at temperatures up to 1100 F solution heatreatment of 1625 - 1850 F plus precipitation heatreat at 1200 - 1400 F provide optimum properties. For spring applications over same temperature range higher strengths are attainable through cold work prior to precipitation heatreatment. Parts which are used at temperatures above 1100 F are afforded optimum properties by solution heatreatment of 2100 F plus stabilization and aging treatments at 1550 F and 1300 F, respectively. Specific heatreatments provided for in specifications are as follows:

AMS 5542, AMS 5582, PWA 1031, PWA 1063	Mill anneal: 1900 - 2000 F for 15 - 20 min., air cool (specification condition)** Precipitation: 1300 F ± 25 for 20 hr, air cool	
AMS 5667	Equalized: 1625 F ± 25 for 24 hr, air cool (specification condition) Precipitation: 1300 F ± 25 for 20 hr, air cool	
AMS 5668	Solution heatreated: 2100 F ± 25 for 2 - 4 hr, air cool Stabilization: 1550 F ± 25 for 24 hr, air cool or furnace cool to or below 1300 F Precipitation: 1300 F ± 25 for 20 hr, air cool	
AMS 5698 (No. 1 temper)	Cold worked 15 - 20% (specification condition) Precipitation: 1350 F ± 25 for 16 hr, air cool	700 - 1000 F service
AMS 5699 (spring temper)	Cold worked 50 - 65% (specification condition) Precipitation: 1200 F ± 25 for 4 hr, air cool	RT - 700 F service
	Cold worked 50 - 65% (specification condition) Full heatreatment like AMS 5668	1000 - 1300 F service

Sulfur-free protective atmospheres recommended for solution heatreating of material which will not be subsequently machined all over.

**Air cooling after solution heatreat or mill anneal is considered adequate for normal subsequent heatreat response; where optimum forming characteristics are desirable, oil or water quench is recommended.

AMS 5542 AMS 5582 AMS 5667 AMS 565[illegible]
AMS 5698 AMS 5699 PWA 1031 PWA 1063

GENERAL INFORMATION (cont.)

FORGEABILITY: Fair to good. Similar to PWA 1003 (Incoloy 901) and superior to that of PWA 1007 (Waspaloy). Usually forged within 2250 F to 1600 F range.

FORMABILITY: Good forming abilities in annealed or solution heatreated condition; comparable to PWA 1030 (Waspaloy) and PWA 1033 (Inconel 718) but inferior to AMS 5525 (A-286) and the austenitic stainless steels. Annealed sheet can be bent 180 deg around a diameter equal to its nominal thickness at room temperature. Solution heatreat at 1925 F for 7 - 10 minutes and air cool after severe forming operations.

MACHINABILITY: Difficult. Machined with same techniques and degree of difficulty as PWA 1030 and PWA 1033; more difficult to machine than austenitic stainless steels. Machinable in all conditions; fully heatreated condition is preferred for finish machining.

WELDABILITY: Difficult. Weldable by either resistance or fusion methods. Fusion welded by either gas tungsten-arc or inert gas metallic-arc process with parent metal filler material. Welding by any method is generally done in the solution heatreated condition. Solution heatreatment of 1800 F for 1 hr, air cool plus precipitation heatreat of 1350 F for 16 hours required after welding. Comperable to AMS 5525 (A-286) and PWA 1030 (Waspaloy), and more difficult than PWA 1033 (Inconel 718).

BRAZEABILITY: Can be silver, copper, nickel, and gold-nickel brazed. Faying surfaces of brazed joints should be nickel plated prior to brazing. Because of heatreat complexities of alloy, special metallurgical considerations are required to ensure desired properties in the finished brazements.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: General resistance to corrosion in gas turbine engine atmospheres is good. Stress-corrosion cracking is a possibility when subjected to certain tensile stresses in the presence of halides.

OXIDATION RESISTANCE: Good resistance to atmospheres encountered in gas turbine engines at temperatures up to approximately 1800 F.

PWA 1009 PWA 1010 PWA 1033

GENERAL INFORMATION

SPECIFICATIONS: PWA 1009 (Dev) PWA 1010 (Dev) — PWA 1033 (Dev)

FORMS: Bars, forgings, welded rings, forging stock — Sheet, strip, plate

CONDITION: PWA 1009 - solution heatreated
PWA 1010 - Bars and forgings - solution and precipitation heatreated
Other forms - as ordered
PWA 1033 - annealed (1750 F for 30 min., air cool or faster)

COMMON DESIGNATIONS: Inconel 718

MELTING PRACTICE: Multiple melting using vacuum consumable electrode process in the remelt cycle, or vacuum induction plus consumable electrode remelt, or vacuum induction melt.

GENERAL DESCRIPTION: Inconel 718 is a heatreatable nickel-base alloy which has good strength at temperatures up to 1100 - 1300 F, and good oxidation and corrosion resistance in gas turbine engine atmospheres up to approximately 1800 F. Yield strength is superior to that of PWA 1003 (Incoloy 901), and PWA 1005 (Waspaloy) up to 1300 F. Stress-rupture and 0.1% creep strengths are superior to those of PWA 1003 up to 1850 F, but inferior to those of PWA 1005 above 1100 F. Weldability is superior to that of Inconel X or Waspaloy, particularly where joints of high restraint are involved. Alloy forges and machines somewhat like PWA 1003.

APPLICATIONS: Parts requiring high strength, good weldability, and good corrosion and oxidation resistance at temperatures up to 1100 - 1300 F. Particularly applicable to compressor components.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Cb + Ta	Mo	Ti	Al	B	Mn	Si	P	S	Ni	Fe
.05%	19	5.3	3	0.9	0.6	.006*	.35*	.35*	.015*	.015*	52.5	remainder

*Maximum

HEATREATMENT:
Solution: 1750 F for 1 hour, air cool or faster
Precipitation: 1325 F for 8 hours, furnace cool (100 F/hr) to 1150 F, hold at 1150 F for 8 hours and air cool.
Sheet and parts not to be machined all over after heatreatment require a protective atmosphere for solution heatreatment.

FORGEABILITY: Fair to good characteristics. More readily forgeable than PWA 1005 (Waspaloy) and PWA 1008 (Astroloy).

FORMABILITY: Good forming abilities in solution heatreated condition; comparable to PWA 1030 (Waspaloy). Sheet under 0.050 in. can be bent 180 deg around a diameter equal to its thickness at room temperature; sheet thicknesses of 0.050 - 0.187 in. can be bent around diameters which are twice their thickness.

MACHINABILITY: Difficult. Machined with same general techniques and degree of difficulty as AMS 5668 (Inconel X) and PWA 1003 (Incoloy 901). Machinable in all conditions; fully heatreated condition is preferred for finish machining.

WELDABILITY: Welding is accomplished with same general techniques used for Inconel X and Waspaloy, but with considerably less susceptability to strain cracking. Fusion welding is done in the solution heatreated condition with parent material filler metal (PWA 1081). Full heatreatment recommended after welding to repair heat-affected zone of weld and to achieve optimum properties.

BRAZEABILITY: Can be silver, copper, nickel, or gold-nickel brazed. Because of heatreat complexities of alloy, special metallurgical considerations are required to ensure desired properties in finished brazements. Faying surfaces of brazed joints shall be nickel plated prior to brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Good corrosion resistance; similar to that of Inconel X.

OXIDATION RESISTANCE: Oxidation resistance in gas turbine engine atmospheres is good at temperatures up to 1800 F.

AMS 5660 PWA 1003

GENERAL INFORMATION

SPECIFICATION:	AMS 5660	PWA 1003
FORM:	Bars, forgings	Forgings
CONDITION:	Solution, stabilization and precipitation heatreated	Solution, stabilization, and precipitation heatreated

COMMON DESIGNATION: Incoloy 901

MELTING PRACTICE: AMS 5660 forgings - consumable electrode or induction vacuum melted
bars - air melt permissible
PWA 1003 - consumable electrode or induction vacuum melted

GENERAL DESCRIPTION: AMS 5660 and its higher strength modification, PWA 1003, are austenitic, iron-nickel alloys which achieve optimum properties through combination heatreat (solution, stabilization, and precipitation). Yield strengths of alloys are substantially reduced at temperatures above 1400 F. Stress-rupture and creep strengths of alloys are superior to those of AMS 5735 precipitation hardenable steel and AMS 6304 hardenable low alloy steel but inferior to those of PWA 1004 (Waspaloy). Alloys forge and machine with slightly less difficulty than PWA 1004 but are inferior to AMS 5735 and AMS 6304 in these respects. Weldability of alloys is poor. Alloys have oxidation resistance comparable to the austenitic stainless steels and good corrosion resistance.

APPLICATIONS: Parts requiring high strength within temperature range 1000 - 1400 F and/or oxidation and corrosion resistance at temperatures up to approximately 1600 F. Used primarily for discs, shafts, spacers, and tierods.

CHEMICAL COMPOSITION (Nominal):

	C	Cr	Ni	Co	Mo	Ti	Mn	Si	Al	B	Cu	Fe
AMS 5660 -	0.1%*	12.5	42.5	1.0*	6.0	2.67	2.0*	0.6*	0.35*	0.015	0.5*	remainder
PWA 1003 -	0.1%*	12.5	42.5	1.0*	5.75	2.85	0.5*	0.4*	0.35*	0.015	0.5*	remainder

*Maximum

HEATTREATMENT:

	AMS 5660	PWA 1003
Solution:	2000 F ± 25/2 hr/W.Q.	1975 - 2025 F ± 25/2 hr/W.Q.
Stabilization:	1450 - 1500 F ± 15/2 - 4 hr/A.C.	1425 - 1475 F/2 - 4 hr/A.C.
Precipitation:	1325 - 1375 F ± 15/24 hr/A.C.	1300 - 1375 F ± 15/24 hr/A.C.
	(Resulting hardness Bhn 285 - 352)	(Resulting hardness Bhn 302 - 388)

Annealing: Same as solution heatreatment.
Annealing and solution heatreating should be done in slightly reducing atmospheres free from sulfur.

FORGEABILITY: Fair. Superior to PWA 1004 (Waspaloy) nickel base alloy. More difficult than AMS 5735 precipitation hardenable steel and AMS 5616 hardenable, corrosion resistant steel. Usual forging temperature range is 2050 - 1800 F. Preheating recommended for large forgings.

FORMABILITY: Fair. Slightly more difficult in solution heatreated condition than the austenitic stainless steels. Severe deformations may require several intermittent anneals.

MACHINABILITY: Difficult. Rates similar to PWA 1004 nickel base alloy and more difficult than AMS 5735 precipitation hardenable steel and AMS 5616 hardenable corrosion resistant steel. Machinable in all conditions; however, fully heatreated is preferred for finish machining.

WELDABILITY: Difficult. Welding not generally recommended.

BRAZEABILITY: Not usually brazed. Can be silver, copper, and gold-nickel brazed; however, heatreat complexities of alloy require special metallurgical considerations to ensure desired properties of finished brazements.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Excellent resistance to corrosive media commonly encountered in turbine applications. Corrosion resistance similar to that of the austenitic stainless steels.

OXIDATION RESISTANCE: Resists oxidation at temperatures up to 1600 F.

PWA 687 PWA 1004 PWA 1030 PWA 1061

GENERAL INFORMATION

SPECIFICATION:	PWA 1004	PWA 687	PWA 1030	PWA 1061
FORM:	Bars, forgings, rings, forging stock	Bars, forgings, rings, forging stock	Sheet, strip, plate	Welded tubing
CONDITION:	Solution, stabilization and precipitation heatreated	Solution heatreated	Annealed	Under 2.0 in. diam - annealed and cold drawn Over 2.0 in. diam - annealed

COMMON DESIGNATION: Waspaloy

MELTING PRACTICE:
- PWA 1004: Multiple melting using consumable electrode process in the remelt cycle, or vacuum induction melted.
- PWA 687: Multiple melting using consumable electrode process in the remelt cycle, or vacuum induction melted.
- PWA 1030: Multiple melting using vacuum consumable electrode process in remelt cycle or vacuum induction plus consumable electrode remelt, or vacuum induction melted.
- PWA 1061: Vacuum induction or vacuum consumable electrode melted.

GENERAL DESCRIPTION: Waspaloy is a heatreatable nickel-base alloy which has good strength at temperatures up to 1400 - 1500 F, and good oxidation and corrosion resistance in gas turbine engine atmospheres at temperatures up to 1600 F. Tensile strength of subject specification materials are superior to those of Inconel X, and inferior to those of Inconel 718 at temperatures up to 1350 F. Creep-rupture strengths are superior to those of Inconel X and to those of Inconel 718 at temperatures above 1150 - 1200 F. Alloy is weldable; but with no small degree of difficulty. Machines like other precipitation hardenable nickel-base alloys and has forming characteristics like those of Inconel 718.

APPLICATIONS: Parts requiring high strength plus good oxidation and corrosion resistance at temperatures up to 1400 - 1500 F. PWA 687, PWA 1030, and PWA 1061 are applicable to parts which require welding. PWA 1004 used for stationary parts which do not require welding or the higher strengths obtainable with PWA 1005 and PWA 1007.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	Mo	Ti	Al	Zr	B	Fe	Mn	Si	S	Ni
0.06%	19.5	13.5	4.0	3.0	1.4	0.06	0.007	2.0*	0.10* (0.75*)	0.15* (0.75*)	0.015* (0.020*)	remainder

*Maximum, ( ) - values for PWA 1004 and PWA 1061.

HEATTREATMENT:

	PWA 1004 & PWA 687	PWA 1030 & PWA 1061
Anneal:		1975 F ± 25 for 30 min., AC or faster
Solution:	1800 - 1925 F for 4 hr, OQ or WQ	1825 F ± 25 for 2 hr, AC or faster
Stabilization:	1550 F ± 15 for 4 hr, AC	1550 F ± 15 for 4 hr, AC
Precipitation:	1400 F ± 15 for 16 hr, AC	1400 F ± 15 for 16 hr, AC

PWA 1004 and PWA 687 parts which are not subsequently machined all over require a suitable protective atmosphere for solution heatreatment and need only to be rapid air cooled. PWA 1030 and PWA 1061 materials require protective atmosphere for both annealing and solution heatreatment.

FORGEABILITY: Fair, better than that of PWA 1008 (Astroloy), but poorer than that of PWA 1003 (Incoloy 901) or PWA 1010 (Inconel 718). Generally forged within 2050 - 1850 F range.

FORMABILITY: Good forming abilities in annealed or solution heatreated condition; comparable to PWA 1033 (Inconel 718) but inferior to austenitic stainless steels. Sheet under 0.050 in. can be bent 180 deg around a diameter equal to its thickness at room temperature; sheet thicknesses of 0.050 - 0.187 in. can be bent around diameters which are twice their thickness.

MACHINABILITY: Difficult. Machined with same general techniques and degree of difficulty as PWA 1003 (Incoloy 901) and PWA 1010 (Inconel 718); more difficult than the austenitic stainless steels. Machinable in all conditions; fully heatreated condition is preferred for finish machining.

PWA 687 PWA 1004 PWA 1030 PWA 1061

GENERAL INFORMATION (cont.)

WELDABILITY: Difficult. Comparable to Inconel X and A-286 but more difficult than Inconel 718. Can be fusion welded by either inert gas tungsten-arc or inert gas metallic-arc process. Welding is accomplished in the solution heatreated condition with parent metal filler material (PWA 1080). Full heatreatment required after welding to repair heat-affected zone of the weld and to achieve optimum properties.

BRAZEABILITY: Can be silver, copper, nickel, and gold-nickel brazed. Faying surfaces of brazed joints should be nickel plated prior to brazing. Because of heatreat complexities of alloy, special metallurgical considerations are required to ensure desired properties in the finished brazements. In many instances, assemblies are solution heatreated and gold-nickel brazed in the same operation; the resultant assembly requires only stabilization and precipitation heatreats to complete the heatreat cycle.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Good resistance to corrosion in gas turbine engine environments.

OXIDATION RESISTANCE: Good resistance to atmospheres encountered in gas turbine engines at temperatures up to 1600 F for intermittent service and up to 1800 F for continuous service.

PWA 1005 PWA 1007

GENERAL INFORMATION

SPECIFICATION: PWA 1005 | PWA 1007

FORMS: Forgings and forging stock | Forgings and forging stock

CONDITION: Forgings - solution, stabilization, and precipitation heatreated
Forging stock - as ordered by forging manufacturer.

COMMON DESIGNATION: Waspaloy

MELTING PRACTICE: PWA 1005: Multiple melting using consumable electrode process in the remelt cycle or vacuum induction melted.
PWA 1007: Vacuum induction plus consumable electrode melt.

GENERAL DESCRIPTION: Waspaloy is a heatreatable nickel-base alloy which has good strength at temperatures up to 1400 - 1500 F, and good oxidation and corrosion resistance in gas turbine atmospheres up to temperatures of approximately 1600 F. Tensile yield strength is slightly superior to that of PWA 1003 (Incoloy 901), but inferior to that of PWA 1010 (Inconel 718) up to 1350 F, and PWA 1008 (Astroloy). Stress-rupture and 0.1% creep strengths are generally superior to those of PWA 1003 and PWA 1010, but inferior to those of PWA 1008. Forges more readily than PWA 1008 but with more difficulty than PWA 1010 and PWA 1003. Machines like PWA 1003 - easier than PWA 1008.

APPLICATIONS: Parts requiring high strength plus good oxidation and corrosion resistance at temperatures up to 1400 - 1500 F. Particularly applicable to rotating parts in compressor and turbine sections.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	Mo	Ti	Al	Zr	B	Fe	Cu	Mn	Si	S	Ni
0.06%	19.5	13.5	4.0	3.0	1.4	0.07	0.007	2.0*	0.1*	0.75*	0.75*	0.02*	remainder

*Maximum

HEATTREATMENT:
Solution: *1800 - 1925 F for 4 hr, oil or water quench
**1800 - 1925 F for 4 hr (protective atm), air cool or faster
Stabilization: 1550 F ± 15 for 4 hr, air cool
Precipitation: 1400 F ± 15 for 16 hr, air cool

*Forgings to be machined all over
**Forgings not to be machined all over

FORGEABILITY: Fair, better than that of PWA 1008 (Astroloy), but poorer than that of PWA 1003 (Incoloy 901) or PWA 1010 (Inconel 718). Generally forged within 2050 - 1850 F temperature range.

MACHINABILITY: Difficult. Machined with same general techniques and degree of difficulty as PWA 1003 and PWA 1010. Machinable in all conditions; fully heatreated condition is preferred for finish machining.

WELDABILITY: Difficult. PWA 687 (Waspaloy in solution heat treated condition) generally recommended when welding is required; see Section 7.22.

BRAZEABILITY: Not usually brazed. Can be silver, copper, and gold-nickel brazed; however, heatreat complexities of alloy require special metallurgical considerations to assure desired properties of finished assemblies.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Good corrosion resistance in gas turbine engine atmospheres.

OXIDATION RESISTANCE: Good resistance to atmospheres encountered in gas turbine engines at temperatures up to 1600 F.

PWA 1008   PWA 1013

GENERAL INFORMATION

SPECIFICATION: PWA 1008 | PWA 1013

FORM: Forgings and forging stock | Forgings and forging stock

CONDITION: Solution, stabilization, precipitation heatreated

COMMON DESIGNATION: Astroloy

MELTING PRACTICE: PWA 1008 - Vacuum induction plus consumable electrode remelt
PWA 1013 - Vacuum induction or vacuum induction plus consumable electrode remelt

GENERAL DESCRIPTION: Astroloy is a heatreatable nickel-base alloy applicable to parts which require high strength, and good oxidation and corrosion resistance at temperatures up to approximately 1500 F. Tensile, creep and stress-rupture strengths are superior to those of PWA 1006 and PWA 1007 (Waspaloy). Fabricability, and oxidation and corrosion resistance of alloy are slightly inferior to those of Waspaloy.

APPLICATIONS: Parts requiring high strengths, and good oxidation and corrosion resistance at temperatures up to approximately 1500 F. Particularly applicable to turbine discs, damper rings and cover plates.

CHEMICAL COMPOSITION (Nominal):

	C	Cr	Co	Mo	Ti	Al	B	Mn	P	S	Si	Fe	Cu	Zr	Ni
PWA 1008	.06%	15.5	17	5.3	3.5	4.5	.02	.15*	.015*	.015*	.2*	.5*	.1*	.06*	remainder
PWA 1013	.06%	15.0	17	5.0	3.4	4.5	.05	.15*	.015*	.015*	.2*	.5*	.1*	.06*	remainder

*Maximum

HEATTREATMENT:

	PWA 1008	PWA 1013
Solution Anneal:	2125 F ± 25/4 hr/AC or faster	
Solution:	1975 F ± 25/4 hr/AC or faster	1975-2075 F ± 15/4 hr/Q in molten salt bath at 600 F ± 10, stabilize 600 F/AC
Stabilization;	1550 F ± 15/4 hr/AC or faster	1600 F ± 15/24 hr/AC to RT + 1800 F ± 15/4 hr/AC
Precipitation:	1400 F ± 15/16 hr/AC or faster	1200 F ± 15/24 hr/AC to RT + 1400 F ± 15/8 hr/AC

Annealing - Same as solution heatreatment.

FORGEABILITY: Fair in small sizes; difficult in large (12" diameter) sizes. Somewhat more difficult to forge than PWA 1006 and PWA 1007 (Waspaloy).

FORMABILITY: Fair. Comparable to Waspaloy and more difficult than the austenitic stainless steels. High rate of work hardening necessitates intermittent anneals for severe deformation operations.

MACHINABILITY: Difficult. Machining accomplished with same general techniques used for PWA 1005 and PWA 1007 (Waspaloy), but with slightly more difficulty. Machinable in all conditions; however, fully heatreated condition is preferred for finish machining.

WELDABILITY: More difficult to weld than Waspaloy. Not generally recommended.

BRAZEABILITY: Not usually brazed. Can be silver, copper, and gold-nickel brazed; however, heatreat complexities of alloy require special metallurgical considerations to ensure desired properties of finished brazements.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Good corrosion resistance in gas turbine engine atmospheres.

OXIDATION RESISTANCE: Good resistance to atmospheres encountered in gas turbine engines at temperatures up to approximately 1600 F.

PWA 658

GENERAL INFORMATION

SPECIFICATION: PWA 658

FORM: Investment castings

CONDITION: Blade and vane castings are thermal shock tested (2000 F for 20 minutes, air cooled) twice. Parts other than blades and vanes - as cast.

COMMON DESIGNATION: IN 100

MELTING PRACTICE: Vacuum melted and cast

GENERAL DESCRIPTION: Cast nickel-base alloy used in the as-cast condition. Stress-rupture and creep strengths of alloy are comparable to those of PWA 659 (SM 200) and superior to those of PWA 655 (Inco 713), PWA 1011 (Nimonic 115), and PWA 689 (U-700). Sulfidation-oxidation resistance, like that of PWA 659, is poor; deterent coatings required for applications at temperatures above 1400 F.

APPLICATION: Primarily turbine blades and vanes.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	Mo	V	Ti	Al	Fe	B	Zr	Ni
0.17*	9.5	15.0	3.0	0.95	5.0	5.5	1.0*	0.015	0.06	remainder

*Maximum

HEAT TREATMENT: Turbine blades - Aged at 1600 F ± 25 for 12 hr, air cooled.

CASTABILITY: Fair, similar to PWA 659 (SM 200).

MACHINABILITY: Difficult. Machining accomplished with same general techniques and degree of difficulty as PWA 655 (Inco 713), PWA 689 (U-700), and PWA 659 (SM 200).

WELDABILITY: Difficult. Not usually welded.

CHEMICAL PROPERTIES

CORROSION AND OXIDATION RESISTANCE: General corrosion resistance of alloy is good. Alloy is subject to sulfidation-oxidation deterioration when operating in gas turbine engine atmospheres which contain certain sulfur-halide combinations at temperatures above 1400 F. In atmospheres where either sulfur or halides are absent, alloy is capable of resisting oxidation at temperatures up to approximately 1800 F. Since presence of deleterious sulfur-halide combinations are quite common in air-propulsion applications, sulfidation-deterent coatings are required for all turbine blade and vane applications of this alloy.

PWA 659

GENERAL INFORMATION

SPECIFICATION: PWA 659

FORM: Investment castings

CONDITION: Blade and vane castings are thermal shock tested (2000 F for 20 minutes, air cooled) twice. Parts other than blades and vanes - as cast.

COMMON DESIGNATION: SM 200

MELTING PRACTICE: Vacuum melted and cast

GENERAL DESCRIPTION: Cast nickel-base alloy used in the as-cast condition. Stress-rupture and creep strengths of alloy are comparable to those of PWA 658 (IN 100) and superior to those of PWA 655 (Inco 713), PWA 1011 (Nimonic 115), and PWA 689 (U-700). Sulfidation-oxidation resistance, like that of PWA 658, is poor; deterrent coatings are required for applications at temperatures above 1400 F.

APPLICATIONS: Primarily turbine blades and vanes.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	W	Cb	Al	Ti	Fe	B	Zr	Ni
0.15*	9.0	10.0	[illegible]	1.0	5.0	2.0	1.5*	0.0[illegible]	0.[illegible]	remainder

*Maximum

HEAT TREATMENT: Turbine blades - aged at 1600 F ± 25 for 50 hr, air cooled.

CASTABILITY: Fair. Similar to PWA 658 (IN 100).

MACHINABILITY: Difficult. Machining accomplished with same general techniques and degree of difficulty as PWA 655, PWA 689, and PWA 658.

WELDABILITY: Difficult. Not usually welded.

CHEMICAL PROPERTIES

CORROSION AND OXIDATION RESISTANCE: General corrosion resistance of alloy is good. Alloy is subject to sulfidation-oxidation deterioration when operating in gas turbine engine atmospheres which contain certain sulfur-halide combinations at temperatures above 1400 F. In atmospheres where either sulfur or halides are absent, alloy is capable of resisting oxidation at temperatures up to approximately [illegible] F. Since presence of deleterious sulfur-halide combinations are quite common in air-propulsion applications, sulfidation-deterrent coatings are required for all turbine blade and vane applications of this alloy.

PWA 663

GENERAL INFORMATION

SPECIFICATION: PWA 663 (Development)

FORM: Investment castings

CONDITION: Blades are thermal shock tested (2000 F for 20 minutes, air cooled) twice. Non-blade applications - as cast

MELTING PRACTICE: Vacuum melted and cast

GENERAL DESCRIPTION: PWA 663 is a cast nickel-base alloy which has strength and oxidation resistance comparable to that of PWA 659, but slightly better ductility. Although oxidation resistance is very good, marginal sulfidation resistance will probably necessitate coating protection. Castability is considered good.

APPLICATIONS: Primarily applicable to turbine blades and vanes.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Co	Mo	Ta	Al	Ti	Fe	B	Zr	Ni
0.10%	8.0	10.0	6.0	4.3	6.0	1.0	.35 max	.015	.07	remainder

HEATREATMENT: Precipitation age - 1650 F ± 25 for 4 hr, air cool

CASTABILITY: Good. Similar to that of PWA 655 (Inconel 713) and significantly better than that of PWA 659 (SM 200) and PWA 658 (IN 100).

MACHINABILITY: Difficult. Accomplished with same general techniques and degree of difficulty as PWA 655, PWA 658, and PWA 659.

CHEMICAL PROPERTIES

OXIDATION AND CORROSION RESISTANCE: General corrosion resistance of alloy is good. Subject to sulfidation-oxidation deterioration when operated at temperatures above 1400 F in gas turbine engine atmospheres which contain certain sulfur-halide combinations. Sulfidation resistance of alloy is reportedly similar to that of PWA 655 (Inconel 713); therefore the alloy will probably require coating protection. General oxidation resistance of alloy is better than that of PWA 659 (SM 200).

PWA 655

GENERAL INFORMATION

SPECIFICATION: PWA 655

COMMON DESIGNATION: Inconel 713c, Haynes Alloy 713c

AVAILABLE FORM: Investment castings

CONDITION: As cast

MELTING PRACTICE: Vacuum melted, vacuum cast

GENERAL DESCRIPTION: Cast nickel base alloy normally used in as cast condition. Minimum 100 hr stress-rupture and 1.0% creep strengths at 1650 F are 33.0 ksi and 23.0 ksi, respectively. Stress-rupture and creep strengths of alloy are superior to those of U-700 but inferior to those of SM 200, IN 100, and PWA 663. Oxidation resistance of alloy is good to 1900 F. Thermal shock properties are superior to those of most commonly used heat resistant nickel base alloys. Alloy is subject to sulfidation; better than IN 100, SM 200 and PWA 663 but inferior to U-700 and Waspaloy.

APPLICATIONS: Turbine blades and vanes.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Mo	Cb + Ta	Ti	Al	B	Zr	Ni + Co
0.20% max	14.0	4.5	2.0	1.0	6.0	0.01	0.08	remainder

HEATREATMENT: Normally used in as cast condition.
Stress relief: 1600 F for 2 hr, air cool.

CASTABILITY: Good, vacuum melting and casting required to maintain control of reactive alloy elements (Ti, Al). Air and inert gas atmosphere melted and cast products are substantially inferior.

MACHINABILITY: Difficult. Comparable to IN 100, SM 200, PWA 663. Use of carbide tools with slow speeds and light loads recommended. Finishing done by careful grinding.

WELDABILITY: Difficult, not generally welded. PWA experience limited to hardfacing of turbine blade shrouds with PWA 694 (wear resistant cobalt base alloy). Post weld stress relief required.

BRAZEABILITY: No data available.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Generally good; but, marginal resistance to sulfidation makes use of a protective coating (PWA 47-14L) desirable.

OXIDATION RESISTANCE: Good up to 1900 F.

PWA 653

GENERAL INFORMATION

SPECIFICATION: PWA 653

COMMON DESIGNATION: WI-52

AVAILABLE FORMS: Investment castings

CONDITION: As cast

MELTING PRACTICE: Air melt, air cast

GENERAL DESCRIPTION: Cast cobalt base alloy generally used in as cast condition. Minimum 100 hour stress-rupture and 1.0% creep strengths at 1700 F are 17.0 ksi and 18.0 ksi, respectively. Stress-rupture and creep strengths of alloy are comparable to those of PWA 657 and substantially superior to those of AMS 5382 and AMS 5385 cast cobalt base alloys. Alloy exhibits good thermal shock and corrosion resistance. Oxidation resistance is poorest of cast cobalt base blade and vane alloys. Protective oxidation and erosion resistant coatings required for applications in vicinity of 1800 F.

APPLICATIONS: Turbine vanes.

CHEMICAL COMPOSITION (Nominal):

C	Cr	W	Cb + Ta	Fe	Co
0.45%	21.0	11.0	2.0	2.0	remainder

HEATTREATMENT: Normally used in as cast condition.
Stress relief: 1600 F ± 25 for 2 hr, air cool

CASTABILITY: Good; similar to AMS 5382.

MACHINABILITY: Difficult; similar to AMS 5382 and PWA 657.

WELDABILITY: Difficult, not generally recommended; however, can be accomplished with special techniques. Stress relief required after welding.

BRAZEABILITY: No data available.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Good.

OXIDATION RESISTANCE: Good up to 1600 F. Protective oxidation and erosion resistant coatings required for applications at temperatures of 1800 F and above.
PWA 45 and PWA 44 protective coatings improve oxidation resistance in 1800 - 2000 F range.

AMS 6415 AMS 6359

GENERAL INFORMATION

SPECIFICATION:	AMS 6415	AMS 6359
AVAILABLE FORMS:	Bars, forgings	Plate, sheet, strip

CONDITION: Bar: Hot or cold finished
Forgings: As ordered
Sheet: Annealed (Rc 25 max) or normalized and tempered (Rc 30 max)

COMMON DESIGNATION: AISI 4340, SAE 4340

MELTING PRACTICE: Generally air melted in electric furnace. Vacuum melted material is also available.

GENERAL DESCRIPTION: AISI 4340 is a low alloy steel which is heatreatable over a wide range of yield strengths - 100 to 210 ksi. Most commonly heatreated to 140 - 195 ksi (Rc 35 - 45) yield strength level for application at temperatures up to 700 F. Yield strength (0.2% offset) of alloy is slightly higher than that of AMS 5613 (AISI 410) steel at comparable hardness at temperatures up to 800 F. Stress-rupture and creep strengths of alloy are inferior to those of AMS 6304 low alloy steel at comparable hardness levels. Forging, machining, and hardening characteristics are comparable to those of AMS 6304 and superior to those of AMS 5616 (Greek Ascoloy) corrosion resistant steel. Corrosion resistance is poor; comparable to that of AMS 6304 but inferior to that of AMS 5613 and AMS 5616.

APPLICATIONS: Parts requiring high hardenability, high strength, and reasonable toughness at moderate temperatures (up to 700 F). Used primarily for shafts, hubs, and compressor discs.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Ni	Mo	Mn	Si	P	S	Fe
0.40%	0.80	1.80	0.25	0.75	0.27	0.04 max	0.04 max	remainder

HEATREATMENT:
Normalize: 15[illegible] - 1700 F/1 hr per section inch, air cool
Austenitize: 1475 - 1600 F, oil quench. Through hardening attained in section sizes up to 3.0 inches with oil quench.
Temper range: 600 - 1200 F for 2 hours and air cooled. (See temper curve for related properties and tempering temperatures.)
Anneal: 1525 - 1600 F, furnace cool; resulting hardness Bhn 215.
Heatreatment at temperatures above 1000 F requires suitable protective atmosphere to avoid decarburization.

FORGEABILITY: Readily forged; comparable to AMS 6304 low alloy steel and AMS 5613 (AISI 410) hardenable corrosion resistant steel. Usually forged in 2250 - 1950 F temperature range. Generally normalized before subsequent hardening and tempering heatreatments.

FORMABILITY: Fair; cold forming experience very limited. Forms in fully annealed condition somewhat like AMS 5504 (AISI 410).

MACHINABILITY: Fair to good. Similar to AMS 5613 (AISI 410) and AMS 6304 low alloy steel but superior to AMS 5616 (Greek Ascoloy) and the austenitic stainless steels. Optimum condition for rough machining is normalized and tempered to Rockwell C 30 max. Finishing can be performed on material hardened and tempered to any strength and hardness level.

WELDABILITY: Fair to poor. Can be fusion welded; however welding is not generally recommended unless phosphorus and sulfur contents are restricted to 0.015% max.

BRAZEABILITY: Readily brazed by all methods. Gold-nickel and copper brazing should precede hardening and tempering. Heatreatment required after AMS 2665 high temperature silver brazing; no heatreatment necessary after AMS 2665 low temperature silver brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Poor corrosion resistance. Protective coating of cadmium plate is required for applications at temperatures up to 500 F. Above 500 F, diffused nickel-cadmium (AMS 2416) plate is used.

OXIDATION RESISTANCE: Poor to fair; not rust resistant. Forms thin adherent oxide film in dry air at temperatures up to approximately 700 F. Scaling becomes appreciable above 1000 F. Comparable to AMS 6304 but inferior to AMS 5613 (AISI 410) and AMS 5616 (Greek Ascoloy).

AMS 6304

GENERAL INFORMATION

SPECIFICATION: AMS 6304

FORM: Bars, forgings

CONDITION: Bar - machinable; Bhn 229 max if cold finished
Forgings - annealed; Bhn 241 max

COMMON DESIGNATION: 17-22-A; Tomplex

MELTING PRACTICE: Electric furnace, air melt.

GENERAL DESCRIPTION: AMS 6304 is a low alloy steel which is generally used in the normalized and tempered condition for maximum elevated temperature strength. Yield strength (0.2% offset) at temperatures above 600 F for AMS 6304 hardened to Rc 35 is superior to that of AMS 6415 low alloy steel and AMS 5616 (Greek Ascoloy). Creep strengths are superior to those of AMS 5616 (Greek Ascoloy) and AMS 6415 (low alloy steel) but inferior to those of AMS 5735 (A-286) or AMS 5660 and PWA 1003 (Inco 901). Forgeability and machinability are like AMS 6415 and superior to AMS 5616 and AMS 5735. Corrosion resistance is poor; similar to AMS 6415, but inferior to AMS 5616. Protection against oxidation is required at temperatures above 750 F.

APPLICATIONS: Parts requiring rupture and creep strengths superior to those of other low alloy and hardenable corrosion resistant steels at temperatures up to 1000 F. Used primarily for compressor discs, spacers, and shafts, and for high temperature bolts.

CHEMICAL COMPOSITION (Nominal):

C	Cr	Mo	V	Mn	Si	P	S	Fe
0.45%	0.95	.55	0.30	0.55	0.27	0.025*	0.025*	remainder

*Maximum

HEATREATMENT:
- Normalize: 1750 F for 1 - 1.5 hr, air cool
- Temper: 1100 F min. for 6 hr, air cool. (Large forgings require additional temper of 1100 F for 4 hr, air cool)
- Process anneal: 1250 F for ½ hr, air cool
- Full anneal: 1450 F for 1 hr per section inch, furnace cool 20 deg F per hr to 1000 F, air cool (Hardness Bhn 160 - 190)

Normalize and anneal heatreatments require suitable protective atmosphere to avoid decarburization.

FORGEABILITY: Readily forged; similar to AMS 6415 low alloy steel. Superior to AMS 5735 (A-286), PWA 1003 (Inco 901) and PWA 1005 (Waspaloy). Usual forging range - 2250 F down to 1600 F.

MACHINABILITY: Fair to good. Similar to AMS 6415 and superior to the austenitic stainless steels.

WELDABILITY: Fair to poor. Not usually welded: however, with some chemistry modifications material can be satisfactorily welded by techniques used for other high strength, low alloy steels.

BRAZEABILITY: Readily brazed by all methods. Gold-nickel and copper brazing should precede normalize and temper heatreatments. Heatreatment required after AMS 2668 high temperature silver brazing; no heatreatment necessary after AMS 2665 low temperature silver brazing.

CHEMICAL PROPERTIES

CORROSION RESISTANCE: Poor; similar to AMS 6415. Protective coating of cadmium plate required for applications at temperatures up to 500 F. Above 500 F diffused nickel-cadmium plate (AMS 2416) is used.

OXIDATION RESISTANCE: Poor to fair; not rust resistant. Forms thin adherent oxide film in dry air at temperatures up to approximately 700 F. Scaling becomes appreciable above 1000 F. Comparable to AMS 6415 but inferior to AMS 5613 (AISI 410) and AMS 5616 (Greek Ascoloy).